DIGITAL PROTECTION OF TRANSMISSION LINE

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Dedicated

To my family

29.5.85

CERTIFICATE

Certified that this work entitled DIGITAL PROTECTION OF TRANSMISSION LINE by Siya Ram has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

May, 1985

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ABSTRACT

The present day EHV/UHV power system network requires highly reliable, sensitive, selective and fast protective schemes. The overcurrent relays were replaced gradually by distance relays for transmission line protection due to their inherent drawbacks. The static relays using solid state components were installed in sixties. The first idea of employing digital computer for the protection of power system networks was proposed during 1969. Till today, a number of computer oriented real-time protection algorithms have been proposed. In this thesis, the overview of the digital computor distance relaying algorithms developed uptill now has been presented in brief. The predictive calculation of the impedance from the relay location to the point of fault is presented and tested for several faults, a good accuracy has been obtained in the impedance calculation. Different types of protective schemes have been realized and tested by digital simulation.

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CHAPTER 1

INTRODUCTION

Power system network is becoming more and more complex today thus requiring the protection schemes that are highly reliable, sensitive, selective and also, fast in operation. A transmission line which is the link between the source and the load at EHV/UHV level requires special attention in the field of protection. In the past, over-current relays were generally used for the protection of the transmission lines. But, these relays are being replaced gradually by distance relays due to certain demerits such as, change of balance point with the type of faults, change in generation capacity and, switching operations etc. Of the several electromechanical measuring units available, the induction cup unit proved to be the best, because of several advantages. However, with the advent of semiconductors, the static relays using solid state components were installed in sixties. The static relays possess several mertis such as, greater sensitivity, lower burden, fast in operation, absence of contacts and mechanical motion and hence less maintenance and immunity from vibrations and shocks due to external causes such as movement, electric locomotives, earthquakes etc. The

static relays are being used increasingly in recent years, particularly for the protection of EHV/UHV systems where increased sensitivity, reliability and speed are important. Use of ICs in place of transistors and discrete components leads to compact, simpler, more reliable and economical relay unit. Studies have shown that a given power system can transmit larger amount of power without loss of synchronism, i.e. stability when a fault is cleared in a shorter time. With the advent of fast operating relays and fast acting CBs, now, it is possible to remove a fault on a transmission line within two cycles (i.e. 40 ms). Higher speed clearing of faults also minimizes the possibility of permanent damage to the components, fire and human risks etc.

Digital computers have been applied to both off line and on-line tasks pertaining to power system studies (load flow, short circuit and stability), control and operation. However their use for the protection of the power system networks is of recent origin, the first idea was proposed during 1969 in this field. Till today, a member of computer oriented real-time protection algorithms have been proposed. Extraction of the fundamental components from the complex post-fault waveforms with the aid of analog and/or digital filters is necessary with

the above algorithms. The digital computer protection of the transmission lines possesses several mertis such as flexibility, i.e. any desired threshold characteristic can be obtained with the same hardware or with the minimum changes in the hardware, self checking properties, adaptive capability and data interface access facilities.

In this thesis, the overview of the digital computer distance relaying algorithms developed uptill now has been presented in brief. Out of the several algorithms proposed, one of them is presented in detail and also tested on DEC 1090 at IIT Kanpur for different possible faults and all possible threshold characteristics have been developed.

The use of digital computers and microprocessors for protective relaying purposes has been drawing the attention of researchers and protection engineers since late 1960's. G.D. Rocbefeller [1] in 1969, proposed a complete groups of algorithms for the protection of the transmission line and other power system components using digital computers. The algorithms proposed up till now can be classified into two categories, distance relay algorithms and travelling-wave relay algorithms. The distance relay algorithms involve the determination of impedance, from the relay location to the point

of fault, from the fundamental components of voltage and current which are extracted from complex post-fault waveforms by analog and/or digital filters. The travelling-wave relay algorithms utilize the complex post-fault waveforms as they are, for making relaying decisions by means of travelling wave techniques. Slemon et al [2] and Ramamoorty [3] described the determination of the fundamental components in phasor form from an ensemble of samples collected over one full cycle by using Fourier Analysis technique. Mann and Morrison [4] described the predictive calculation of impedance and its phase angle from a much fewer number of samples of voltage and current and their time derivatives, in another paper [5], they proposed a relaying of a three phase line using this technique.
P. Gokul et al [6] described the predictive calculation of impedance and its phase angle and also quadrilateral characteristic was realised. The predictive technique was presented also by Gilcrest et al [7] who proposed the use of first and second time derivatives of the samples, and, by Gilbert and Shovlin [8] who proposed the use of samples and sampling interval. Cars and Jackson [9] described the use of two digital orthogonal notch filters with sine characteristics to determine the magnitude and phase angle of the fundamental components from samples taken at four equally spaced time intervals over the fundamental

period, and, the use of an analog low pass RC filter with a cut off frequency of 85 Hz to band limit the voltage and current signals prior to sampling. Hope and Umamaheswaran[10] described the use of odd and even square waves, besides sine cosine functions, for the extraction of fundamental frequency components. Hope et al [11] and Thirupathaiah et al [12] have also employed Fourier Analysis techniques with one cycle data window, whilst Phadbe et al [13,14], and Wisznicwski [15] and, Sunnak et al [16] have employed these techniques with half a cycle data window. Some authors proposed the transmission line modelling by a series R-L circuit, the numerical solution of the differential equations provides the value of R and L. McInnes and Morrison [17] proposed the integration of the defferential equations over two successive sampling intervals to generate adequate number of equations to solve for R and L, and used the trapezoidal rule to evaluate the integrals. Poncelet [18], and Bornard and Bastide [19] treated the deficiency in this modelling as an error and solved for R and L subject to the minimisation of the sum of squares of these errors over a certain number of successive sampling intervals. Smolinski [20] modelled the transmission line by a single Pi section-including the shunt parameters, and solved the resultant differential equations by replacing them by finite differences and

using four sample sets to obtain the value of R and L. In the above modelling, the filtering is not needed as the cause of h.f. transients, shunt capacitors, has been included in the modelling. Ranjbar and Cory [21] presented a digital harmonic filter in which the integration is carried out over a certain member of overlapping subintervals with preset limit while the differential equations are being solved by numerical integration method. Sachdev and Baribean [22] assumed the post fault waveform to be comprising of a decay D.C. offset, the fundamental and a certain numbers harmonicc and determined the fundamental component by applying the least square error method. Johns and Martin [23] presented a finite transform method in which the fundamental frequency impedance can be determined by carrying out the filtering process in the frequency domain. Girgis and Brown [24, 25] developed two state and three state Kalman filters to extract the fundamental voltage and current phasor respectively, and reported, that, the error involved is less than one percent after half a cycle. Sanderson and Wright [26] have dealt with series compensated lines. They modelled the line bya series RLC circuit and solved the resultant differential equations by integrating them over three successive sampling intervals.

Vitin's correlation method based on travelling wave theory [27] is suitable for computer application also. Takagi and Yamakosi [28] described the microcomputer application of the differential current relay [29] whose operation is based on the travelling wave theory. Deshikachar and L.P. Singh[30] developed the relaying algorithm based on travelling wave phenomena, which is very fast in operation.

Now, a chapterwise description of the work carried out and reported in this thesis is given below.

Chapter two presents the distance relay algorithms proposed by several authors and also the theory and principles of filters to extract the fundamental components from the post fault waveforms which, in general, are not sinusoidals as they contain in addition to the fundamental components, d.c. offset and transients components also.

Chapter three deals with the digital simulation of a proposed three phase relaying scheme with all possible threshold characteristics.

Finally, chapter four concludes with the findings of the present work and scope for future extension.

CHAPTER 2

DIGITAL RELAYING SCHEMES OF TRANSMISSION NETWORKS

2.1 INTRODUCTION

The need, for fast and reliable protective relaying schemes for transmission lines, especially at EHV/UHV voltage level was felt a long back. In fact, the installation of minicomputers and microprocessors for the purpose of protection of power system networks, which is a step in this direction, is going to be reality in near future. Digital protection of transmission lines possesses several merits such as faster relay operation and flexibility to obtain any type of desired threshold characteristics with the same hardware or with the minimum changes in hardware and also self checking against any failure in hardware.

The work in the field of protection of power system networks using digital computer was started in late 1960s and since then, a number of algorithms have been proposed for the protection of transmission lines. The algorithms proposed so far can be classified into two groups;

1. distance relay algorithm based on fundamental voltage and current,
2. travelling wave relay algorithm based on travelling wave phenomenon.

Both these algorithms need appropriate type of filter and filtering circuit which is being discussed in the following paragraph.

2.2 FILTERING

The post fault waveforms, during the first one or two cycles following the occurance of a fault, comprise of a power frequency fundamental component along with an exponentially decaying d.c. component as well as high frequency transients. In addition, if the line fault is near generating station, the post fault line voltage and current waveforms will also contain subtransient and transient power frequency components. The distance relaying algorithms involve in computing the power frequency impedance between relay location and the point of fault from the fundamental components of voltage and current obtained by suppressing other components through analog and/or digital filters and line modelling. This filtering introduces a time delay in relay operation. Analog and digital filters, which have been proposed and/or being used for this purpose, are described in the following sections.

2.2.1 Analog Filters - [4]

Iron cored current transformers with resistive burdens transmit the full amount of offset in the primary fault current.

This component often takes more than 5 cycles to decay on the present systems with high X/R ratios. The voltage can also have an offset component, but this is considerable smaller than that on the current waveform. The relevent expressions are well known [32] and are repeated here for convenience,

$$i_1 = I_{1pk} \quad \sin(wt+\alpha-\varphi_1) - e^{-R_1 t/L_1} \sin(\alpha-\varphi_1) \tag{2.1}$$

$$v_1 = V_{1pk} \sin(wt + \alpha - \varphi_1 + \varphi_L) - \frac{\sin(\alpha-\varphi_1)\sin(\varphi_1-\varphi_L)}{\sin\varphi_1} e^{-R_1 t/L_1} \tag{2.2}$$

In these equations, α is the phase of fault incidence, the subscript 1 refers to primary (system) quantities, and L refers to line quantities.

If an ideal C.T. is connected to a secondary burden having the same X/R ratio as the primary circuit, then the voltage across the burden will be purely sinusoidal.

For a C.T. of secondary burden R_2 and L_2,

$$v = -\frac{N_2}{N_1}(i_1 R_2 + L_2 \frac{di_1}{dt}) \tag{2.3}$$

where subscript 2 refers to CT secondary.

From above equation, the coefficient of the exponential term is zero if,

$$\frac{X_1}{R_1} = \frac{X_2}{R_2} \tag{2.4}$$

Thus, dc offset in the current signal can be eliminated using mimic impedance in the CT secondary, to match primary X/R ratio to that of the secondary. But, the exact cancellation of the dc offset is not possible for all faults. The primary X/R ratio to be matched is that of source plus line to the fault point, and since in general, the source X/R is not equal to the line X/R, the overall primary X/R is a variable quantity, dependent on, how far, along the line the fault occurs.

RC low pass filters, with a suitable cut off frequency, have been used to eliminate the high frequency components in conjunction with some of the algorithms [7.8]. The value of the highest frequency required is of considerable importance since, it is necessary for

$$f_s \geq 2\, f_{max}$$

where, f_s = sampling frequency and

f_{max} = maximum frequency present in sampled signal.

The cut off or half power frequency f_c, for a simple RC low pass filter, is given by,

$$f_c = \frac{1}{2\pi RC} \tag{2.5}$$

The 10-90% rise time tr of this filter to a step input is given by,

$$\begin{aligned} tr &= RC\,(-\ln 0.1 + \ln 0.9) \\ &= 2.2\ RC \end{aligned} \tag{2.6}$$

Therefore, by combining above two equations (i.e. eqns. 2.5 and 2.6), we get,

$$f_c = \frac{0.35}{tr} \tag{2.7}$$

The minimum rise time required can be determined from an examination of the protection speed requirements.

2.2.2 Digital Filters

The digital filter is a digital system that can be used to filter discrete time signals. It can be implemented by means of software (computer programs) or by means of dedicated hardware, and, in either case, it can be used to filter

real-time signals or non-real time signals. The various types of digital filters, which have been proposed so far, are described below.

2.2.2.1 Notch Filters [9]

The band of frequencies around 50 Hz will be passed by a filter with a 50 Hz sine wave impulse response. The response must be finite in length for obvious reasons and since, truncation points will affect the frequency response, they may be chosen on this basis. For a truncated sinusoid impulse response, the frequency response is given by,

$$H(w) = \int_{-B}^{B} \mathrm{Cos}\,(\Omega t).\ \exp\,(-jwt)\ dt \qquad (2.8)$$

where,

$$B = T_p/2$$

$$= \frac{\sin(1-w/\Omega)\pi p}{(\Omega - w)} + \frac{\sin(1+w/\Omega)\ \pi p}{(\Omega + w)} \qquad (2.9)$$

where

Ω = impulse response sinusoid frequency

and p = number of cycles in impulse response

To eliminate the effects of d.c. offset in fault current it is required that,

$$H(0) = 0 \tag{2.10}$$

which is

$$\frac{2 \sin(\pi p)}{\Omega} = 0 \tag{2.11}$$

That is, the impulse response is restricted to having an integral number of electrical cycles. The high frequency components are eliminated by analog low pass filter.

2.2.2.2 Selected Harmonic Filters

While the differential equations of the line are being solved by numerical integration, the integration is carried out over a certain number of overlapping subintervals with required end points. This results in the elimination of certain harmonics and their multiples.

An equation of the form,

$$v = R\, i_x + L \frac{di_y}{dt} \tag{2.12}$$

is obtained for all fault conditions where the values of v,

i_x and i_y can be found by appropriate choice and combination of sampled voltage and current. In general, it is possible to calculate R and L, so that, any number of harmonics can be eliminated. For example to remove the third harmonic, above equation can be integrated once, over the interval 0, α (α is an arbitrary constant) and over the interval $\pi/3$, $(\alpha+\pi/3)$, the resulting equations, when added give :

$$L\left[\int_0^{\alpha} di_y + \int_{\pi/3}^{\alpha+\pi/3} di_y\right] + R\left[\int_0^{\alpha} i_x\,dt + \int_{\pi/3}^{\alpha+\pi/3} i_x\,dt\right] =$$

$$\left[\int_0^{\alpha} v\,dt + \int_{\pi/3}^{\alpha+\pi/3} v\,dt\right] \qquad (2.13)$$

This equation is solved by numerical methods in which the third harmonic and its multiples are completely filtered.

In general, to remove two harmonics of order m and n and multiples thereof, the resulting equation will be :

$$L\left[\int_0^{2\pi/m} di_y + \int_{\pi/M}^{2\pi/m+\pi/n} di_y\right] + R\left[\int_0^{2\pi/m} i_x dt + \int_{\pi/n}^{2\pi/m+\pi/n} i_x\,dt\right] =$$

$$\left[\int_0^{2\pi/m} v\,dt + \int_{\pi/n}^{2\pi/m+\pi/n} v\,dt\right] \qquad (2.14)$$

2.2.2.3 Least Square Error Filters [13,22]

A formal procedure for smoothing the data is to fit a polynomial of degree m to (2n + 1) samples of data. If $m < (2n+1)$, a least square fit can be obtained. The necessary time derivatives are then estimated by differenciating the polynomial.

A cubic fit over seven points or a quadratic fit over five points or a straight line fit over three points are perhaps necessary to satisfy the redundancy requirement. If a waveform contains a decaying DC offset, the fundamental and a desired number of harmonic components are assumed and the least square error criterion is applied to determine the unknown parameters of the fundamental components.

2.2.2.4 Orthogonal Transform Filters

Of these, the Fourier Transform filter is the most widely used, it suppresses all the unwanted components and therefore, offers the best accuracy, but, it requires a data window of one full fundamental period [2,10]. The orthogonal functions may include the following :

i) sine and cosine function -

The Fourier transform $F_c(s)$ of $\cos \pi x$ is

$$F_c(s) = \int_{-\tau}^{\tau} \cos \pi x \, e^{-j2\pi s x} \, dx \tag{2.15}$$

Since, cos π x is an even function

$$F_c(s) = \int_{-\tau}^{\tau} \cos\pi x \cos 2\pi s \, dx \tag{2.16}$$

Using trigonometric identies and solving, we get,

$$F_c(s) = \frac{1}{2} \text{ sinc } 2(s+\frac{1}{2}) + \frac{1}{2} \text{ sinc } 2(s-\frac{1}{2}) \tag{2.17}$$

where, we define,

$$\text{sinc} s = \frac{\sin\pi s}{\pi s} \tag{2.18}$$

The Fourier transform $F_s(s)$ of $\sin\pi x$ is given by

$$F_s(s) = \int_{-\tau}^{\tau} \sin\pi x \; e^{-j2\pi sx} \, dx \tag{2.19}$$

which can be expressed as,

$$F_s(s) = \frac{j}{2} \text{ sinc } 2(s-\frac{1}{2}) - \frac{j}{2} \text{ sin c } 2(s+\frac{1}{2}) \tag{2.20}$$

Examination shows, that, cosine/sine functions have a high rejection to dc and to high order harmonics.

ii) Even and odd square wave -

The importance of this function in computer relaying is, that, real and imaginary components of the physical

quantity sampled are obtained trough addition rather than multiplication.

The Fourier transform, $F_c(s)$ of the even square wave is,

$$F_c(s) = 2\ \mathrm{sinc}s - \mathrm{sinc}2s \qquad (2.21)$$

The Fourier transform, $F_o(s)$ of odd square wave is,

$$F_o(s) = -2j\ \mathrm{sinc}s.\sin\pi s \qquad (2.22)$$

Examination shows, that, the square wave functions have a high rejection to d.c. and tend to limit high order harmonics.

The properties of Walsh functions and Walsh transformation [31] are used to extract the peak values of fundamental frequency components of the voltages and the currents and then the impedance seen by the relay is computed.

Filters using sine/cosine functions, employing a data window of half cycle and less than half a cycle with tolerable error, have also been proposed [13,15].

2.2.2.5 Finite Transform Filters [23]

The operational relationship given in eqn. (2.23), applies irrespective of the waveforms of voltage and current

for a solid fault in a transmission line :

$$v_r = Z(p)\ i_r \tag{2.23}$$

where, v_r is the instantaneous value of relaying voltage

i_r is the instantaneous value of relaying current

$Z(p)$ is the operational value of fault loop impedance

The voltage v_r can be considered as the summation of an arbitrary number of components v_{r1}, v_{r2} ..., which are chosen, so that, at all times $v_r = v_{r1}+v_{r2}+ \ldots$. Superposition can be used to relate the total current i_r to the components of current which would flow in the circuit in response to the separate application of each of the voltage components; i.e. if the currents that flow in response to the separate application of the voltage components v_{r1}, v_{r2}, ... are i_{r1}, i_{r2}, ... , respectively, the total current is given by

$$i_r = i_{r1} + i_{r2} + \ldots . \tag{2.24}$$

Each pair of components is related by an equation of the form of eqn.(2.23) , and, considering the second component, the time domain relationship of eqn. (2.25) applies :

$$v_{r2} = Z(p)\ i_{r2} \tag{2.25}$$

It is possible to transform eqn. (2.25) from time domain to the frequency domain by means of the Fourier transform integral.

The transformation of eqn.(2.25) into frequency domain, therefore, results in the relationship given in eqn.

$$v_{r2}(jw) = Z(jw)\ i_{r2}\ (jw) \tag{2.26}$$

where,

$$v_{r2}(jw) = \int_{-\infty}^{\infty} v_{r2} \exp\ (-jwt)\ dt \tag{2.27}$$

$$i_{r2}(jw) = \int_{-\infty}^{\infty} i_{r2} \exp\ (-jwt)\ dt \tag{2.28}$$

If, components at a particular extracted frequency are evaluated by means of the Fourier integrals, the fault loop impedance at the particular frequency chosen, is given by eqn. (2.29)

$$Z(jw_e) = v_{r2}(jw_e)/i_{r2}(jw_e) \tag{2.29}$$

If, for example, the component v_{r2} is equal to the relaying voltage v_r for all time inside a window $T_1 \leq t \leq T_2$ and

zero outside, thus window length being (T_2-T_1), $v_{r2}(jw_e)$ is given by,

$$v_{r2}(jw_e) = \bar{v}\,(jw_e) = \int_{T_1}^{T_2} v_r \exp\,(-jwt)\, dt \qquad (2.30)$$

The above equation is referred to as the finite transform of the relaying voltage $\bar{v}_r(jw_e)$

2.2.2.6 Kalman Filters [24, 25]

This method of filtering is especially suited to on-line digital processing because the noisy input (measurement) data is produced recursively. The non fundamental components in the current and voltage waveforms are designated as noise signals. As the noise signals depend upon the location and the type of faults, which are random in nature, the noise signal is considered a random process. The filter is initialized with an initial estimate of signal and its error covariance. Then, as each measurement sample becomes available in real time, it is used to update or refine the filter's previous estimate.

The noise signal in the voltage waveform is considered as a white noise sequence with decreasing variance. A two state Kalman filter is used to extract the fundamental voltage phasor.

The noise signal in the current waveform is considered as an exponential component plus a white noise sequence with decreasing variance. A three state Kalman filter is used to extract the fundamental current phasor. The third state accounts for the exponentially decreasing component. These filters are expressed in the form of state equations.

The error in this filtering process [24,25] has been reported to be less than 1% after half a cycle. The method appears to be suitable for high speed digital computer relaying based on post fault phasor (ie fundamental sinusoidal) quantities.

We now give the overview of the digital distance relaying algorithm.

2.3 DIGITAL DISTANCE RELAYING ALGORITHMS

These algorithms aim at extracting the fundamental power frequency components of voltage and current from the complex post-fault waveforms and then, determining the impedance

from these fundamental components. A number of algorithms have been proposed by several authors [1-23] to calculate fault impedance from the relay location to the point of fault. These algorithms can be grouped into four categories which are described briefly below.

2.3.1 Method 1

In this method, the magnitude of impedance is calculated as the ratio of peak voltage to peak current and its argument as the difference between the phase angles of the voltage and current. A few algorithms based on this method, as proposed by different authors [1-6] are given below.

2.3.1.1 Fourier Analysis Method -

This algorithm was proposed by Ramamoorty [2]. The samples for voltage and current are collected over one full cycle. The calculation of fundamental quantity is done as follows :

$$f_1(t) = \sqrt{a_1^2 + b_1^2}\ \sin\ (wt + \tan^{-1}(\frac{a_1}{b_1})) \qquad (2.31)$$

$$a_1 = \frac{x}{2}(f_o+2f_1\cos x+2f_2\cos 2x+\ldots+f_n\cos nx) \qquad (2.32)$$

$$b_1 = \frac{x}{2}(2f_1\sin x+2f_2\sin 2x+\ldots+2f_{n-1}\sin(n-1)x) \qquad (2.33)$$

where x is the sampling interval (rad) given by $\frac{2\pi}{n}$,

n is the number of intervals in one cycle,

f_o, f_1, f_2 ... f_n are sampled values of input signal over a period of one cycle.

The factors cosx, sinx ... cosnx, sin(n-1)x are constants and can be calculated and stored in the memory apriori as weighting functions on the sample values.

The computation is done for both the voltage and the current, the voltage peak and current peak are calculated and then modulus of impedance and its phase angle are evaluated.

2.3.1.2 Predictive Calculation of Peak Values

The peaks of voltage and current are predicted before their actual occurance from the given samples [4] .

$$\text{Let, } v = V_{pk} \sin wt \tag{2.34}$$

Taking derivative of the equation (2.34), we get,

$$v' = w\, V_{pk} \cos wt \tag{2.35}$$

From these two equations, the peak value of sinusoidal voltage is given by,

$$V_{pk} = \sqrt{v^2 + \left(\frac{v'}{w}\right)^2} \tag{2.36}$$

If current is given by,

$$i = I_{pk} \sin (wt+\varphi) \tag{2.37}$$

Taking derivative of the eqn. (2.37), we get,

$$i' = w I_{pk} \cos (wt+\varphi) \tag{2.38}$$

The peak value of sinusoidal current is,

$$I_{pk} = \sqrt{i^2 + (\frac{i'}{w})^2} \tag{2.39}$$

Impedance modulus is given by,

$$|Z| = \frac{V_{peak}}{I_{peak}} \tag{2.40}$$

Dividing, eqn (2.34) by (2.35)

$$\frac{vw}{v'} = \frac{V_{pk} \sin wt}{V_{pk} \cos wt}$$

$$\tan wt = \frac{vw}{v'}$$

$$wt = \tan^{-1} (\frac{vw}{v'}) \tag{2.41}$$

Similarly, for current sample

$$(wt+\varphi) = \tan^{-1} (\frac{iw}{i'}) \quad (2.42)$$

Thus phase angle between voltage waveform and current waveform is,

$$\varphi = \text{arc tan } (\frac{wi}{i'}) - \text{arc tan } (\frac{wv}{v'}) \quad (2.43)$$

By using central difference theorem or backward difference theorem, the impedance and its angle are evaluated.

The predictation of the voltage peak and the current peak using samples and their first and second derivatives was proposed [7] , and also by using samples and sampling interval [8].

2.3.2 Method 2

In this method, the fundamental components of voltage and current are determined in the phasor form, from which the real and imaginary parts R and X of the psuedo-impedance seen by the relay can easily be evaluated. A few algorithms, based upon this method, are described below.

2.3.2.1 Impedance Calculation based on the Theory of Orthogonal Transform [10]

Since, impedance is a complex function, the digital impedance relay determines the complex value of the physical quantity, current or voltage, by sampling with two orthogonal functions of the variable time. Two sets of such orthogonal functions viz, cosine/sine functions and even odd square wave functions, have been discussed in section (2.2.2.4).

The real axis frequency spectrum is obtained by using the cosine function as a sample function, i.e. real axis transform of physical quantity is multiplied to the Fourier transform $F_c(s)$ of $\cos\pi x$. Similarly, the imaginary axis spectrum is obtained by using sine function as a sample function. Examination shows, that, these functions have a high rejection to dc and to high order harmonics.

If the extraction of fundamental frequency components is done by means of correlating the signal with the sine and cosine function of the Fundamental frequency, and the data window is shorter than one cycle, the presence of a periodic components in the signal give rise to large source of error. To minimize the error in calculating the fundamental component for a data window equal to half cycle, the signals ought to be correlated with sine/cosine function which have period equal

to data window length [16].

Let, current and voltage input signals are,

$$I(t) = I_1 \cos(w_1 t-\alpha)+I_a e^{-(t/T_a)} + I_p e^{-t/\tau_p} \cos(w_p t-r) \quad (2.44)$$

$$V(t) = V_1 \cos(w_1 t-\alpha+ \quad)+V_a e^{-(t/T_a)} +V_p e^{-t/\tau_p} \cos(w_p t-\beta) \quad (2.45)$$

First terms on the right hand side of equations (2.44) and (2.45) are steady state fundamental components. The second terms are well known aperiodic (that is dc) components decaying with time constant T_a. The third term represents decaying oscillations induced by the fault. The real and imaginary parts of voltage and current are calculated for the angular frequency of w_2 corresponding to data window at which the spectrum of aperiodic component reaches minimum. It is known that,

$$V_1 = V_d + j\ V_q \quad (2.46)$$

$$I_1 = I_d + j\ I_q \quad (2.47)$$

Let, $\tau = t - (t_1 + \frac{Tw}{2})$ (2.48)

where t_1 is the beginning of the data window Tw.

According to Fourier Transform theory and correlating the signal with sine/cosine functions which have period equal to data window, Tw, that is $w_2 = \frac{2\pi}{Tw}$, we have,

$$V_d = \frac{K}{Tw} \int_{\frac{Tw}{2}}^{\frac{Tw}{2}} V(\tau) \cos w_2 \tau d\tau \tag{2.49}$$

$$V_q = \frac{P}{Tw} \int_{-\frac{Tw}{2}}^{-\frac{Tw}{2}} V(\tau) \sin w_2 \tau d\tau \tag{2.50}$$

$$I_d = \frac{K}{Tw} \int_{-\frac{Tw}{2}}^{\frac{Tw}{2}} I(\tau) \cos w_2 \tau d\tau \tag{2.51}$$

$$I_q = \frac{P}{Tw} \int_{-\frac{Tw}{2}}^{\frac{Tw}{2}} I(\tau) \sin w_2 \tau d\tau \tag{2.52}$$

where coefficients K and P are,

$$K = \frac{\pi(1 - r^2)}{r \sin \pi r}, \quad P = \frac{-\pi(1 - r^2)}{\sin \pi r} \quad \text{and } r = \frac{w_1}{w_2}$$

Here, w_1 is the normal power frequency of 50Hz, and w_2, the angular frequency corresponding to data window.

Taking data window equal to half the period, that is, half cycle, i.e. $Tw = \frac{\pi}{w_1}$, the coefficients K and P can be written as,

$$K = \frac{3\pi}{2}, \; P = \frac{-3\pi}{4} \tag{2.53}$$

Substituting the values of coefficients K and P in the above equations, and using trapezium method of integration, the values of V_d, V_q, I_d and I_q are evaluated.

The impedance seen by the relay is obtained by dividing the peak of voltage by the peak of current, that is,

$$Z = \frac{V_1}{I_1} = \frac{V_d + j\,V_q}{I_d + j\,I_q}$$

$$Z = \frac{V_d I_d + V_q I_q}{I_d^2 + I_q^2} + j\,\frac{V_q I_d - V_d I_q}{I_d^2 + I_q^2}$$

Since $Z = R + jX$

Therefore,

$$R = \frac{V_d I_d + V_q I_q}{I_d^2 + I_q^2}, \tag{2.54}$$

$$X = \frac{V_q I_d - V_d I_q}{I_d^2 + I_q^2} \tag{2.55}$$

2.3.2.2 Impedance Calculation Using Least Square Fit [12]

An example of a third degree polynomial fit to seven point data is given. The smoothed values of y_o, y_o' and y_o'', for a given data set y_K where, $K = -3, -2, -1, 0, 1, 2, 3$, are given by,

$$\bar{y}_o = \frac{-2(y_{-3}+y_3)+3(y_{-2}+y_2)+6(y_{-1}+y_1)+7y_o}{21} \tag{2.56}$$

$$\bar{y}_o' = \frac{22(y_{-3}-y_3)-67(y_{-2}-y_2)-58(y_{-1}-y_1)}{252} \tag{2.57}$$

$$\bar{y}_o'' = \frac{5(y_{-3}+y_3)-3(y_{-2}+y_2)-4y_o}{42} \tag{2.58}$$

These estimates are then used to determine the phasor representation for $\{y_K\}$

$$y^2 = y_s^2 + y_c^2 \tag{2.59}$$

where, y_s is real component, and y_c is imaginary component of fundamental component y.

$$y^2 \simeq (\bar{y})^2 + \frac{1}{w^2}(\bar{y}')^2$$

$$\simeq \frac{1}{w^2}(\bar{y}')^2 + \frac{1}{w^4}(\bar{y}'')^2$$

$$\simeq \frac{(\bar{y}_1')^2 + (\bar{y}_2')^2 - 2(\bar{y}_1)(\bar{y}_2') \cos (kwt)}{w^2 \sin^2 (kwt)} \tag{2.60}$$

and,

$$\frac{Y_c}{Y_s} \simeq \frac{w(\bar{y})}{(\bar{y}')}$$

$$\simeq \frac{-\bar{y}''}{(w\bar{y}')}$$

$$\simeq \frac{(\bar{y}_1') \cos kwt - \bar{y}_2'}{(\bar{y}_2') \sin kwt} \tag{2.61}$$

where, the subscripts 1 and 2 refer to estimates at sample times t_1 and t_2 such that $(t_1-t_2) = kwt$, k being and integer.

An another algorithm, based on the least error squares curve fitting technique, assumes that input is composed of a fundamental frequency component, a decaying dc and harmonics component of specified order [20]. The fundamental frequency component is determined with the above technique. The real and imaginary components of the voltage and the current are defined as

$$x_{2v} = V_p \cos \theta_v \; ; \; x_{3v} = V_p \sin \theta_v$$

$$x_{2i} = I_p \cos \theta_i \; ; \; x_{3i} = I_p \sin \theta_i$$

The real and imaginary components of the impedance are given as,

$$R = \text{Re}\ (\frac{V}{I})$$

$$= \frac{(X_{2v}\ X_{2i} + X_{3v}\ X_{3i})}{(X_{2i}\ X_{2i} + X_{3i}\ X_{3i})} \qquad (2.61)$$

$$X = \text{Im}\ (\frac{V}{I})$$

$$= \frac{(X_{3v}\ X_{2i} - X_{2v}\ X_{3i})}{(X_{2i}\ X_{2i} + X_{3i}\ X_{3i})} \qquad (2.63)$$

2.3.3 Method 3

In this method, the line is modelled by differential equations, the numerical solution of which yields the value of R and X. The differential equation describing the transmission line (neglecting shunt parameters) is,

$$v = Ri + L\frac{di}{dt} \qquad (2.54)$$

In the above representation, there is no need to suppress the D.C. offset as it is included in the representation of transmission line. A number of algorithm were proposed to solve

the enqn.(2.64)numerically. In 1971, Mc Innes et al. [17] proposed an algorithm in which integration was carried out over two successive time intervals. Integral equations are solved numerically using trapezoidal rule. The final expression for R and L are as shown below :

$$R = \frac{(V_{K-1}+V_K)(i_{K-1}-i_{K-2})-(V_{K-1}+V_{K-2})(i_K-i_{K-1})}{(i_{K-1}+i_K)(i_{K-1}-i_{K-2})-(i_{K-1}+i_{K-2})(i_K-i_{K-1})} \quad (2.65)$$

$$L = \frac{h}{2}\;\frac{(V_{K-1}+V_{K-2})(i_{K-1}+i_K)-(V_{K-1}+V_K)(i_{K-1}+i_{K-2})}{(i_{K-1}+i_K)(i_{K-1}-i_{K-2})-(i_{K-1}+i_{K-2})(i_k-i_{K-1})} \quad (2.66)$$

where 'v' and 'i' are instantaneous value of the voltage and the current, 'K' is the instant and 'h', the time interval. The above euqation assumes perfectly transposed transmission line and, it does not account for the shunt capacitance or series compensation. The fault resistance and the effect of power flow on the transmission line at the moment of a fault is also not considered. The data window is one cycle.

In 1975, Ranjbar and Cory [21] developed another technique, in which particular harmonic and their multiples are eliminated by taking appropriate integration intervals.

This technique has been presented in section (2.2.2).

In 1979, Smolinski [20] proposed an algorithm which accomodates both DC transient offset, transient high frequency components of line voltage and current signals without any additional filtering for these transients. The transmission line model used in this algorithm is a single equivalent π section for the portion of the line from the relay location to the point of fault. The approach used in this algorithm is therefore one of including the sources of transient components of the line voltage and the current signals in the impedance calculation algorithm, rather than one of filtering the transient components out and, the, calculating the impedance of line from the remaining filtered signals.

During post fault conditions, this single equivalent π section model is described by equations (2.67) or (2.68)

$$v = R_L\ (i-i_c) + L_L\ \frac{d(i-i_c)}{dt} \tag{2.67}$$

$$i_c = C\ \frac{dv}{dt}$$

or

$$v = R_L\ i + L_L \frac{di}{dt} - R_L C \frac{dv}{dt} - L_L\ C\ \frac{d^2v}{dt^2} \tag{2.68}$$

By selecting four successive sets of voltage and current samples and replacing the derivatives in equation (2.68) by corresponding finite differences, one gets equation (2.69) from (2.68) for the four sample set.

$$\begin{bmatrix} i_K & \frac{i_{K+1} - i_{K-1}}{2h} & -\frac{(v_{K+1} - v_{K-1})}{2h} & -\frac{(v_{K+1} - 2V_K + V_{K-1})}{h^2} \\ i_{K+1} & \frac{i_{K+2} - i_K}{2h} & -\frac{(v_{K+2} - v_K)}{2h} & -\frac{(v_{K+2} - 2V_{K+1} + v_K)}{h^2} \\ i_{K+2} & \frac{i_{K+3} - i_{K+1}}{2h} & -\frac{(v_{K+3} - v_{K+1})}{2h} & -\frac{(v_{K+3} - 2V_{K+2} + v_{K+1})}{h^2} \\ i_{K+3} & \frac{i_{K+4} - i_{K+2}}{2h} & -\frac{(v_{K+4} - v_{K+2})}{2h} & -\frac{(v_{K+4} - 2V_{K+3} + v_{K+2})}{h^2} \end{bmatrix} \begin{bmatrix} R_L \\ L_L \\ CR_L \\ CL_L \end{bmatrix} = \begin{bmatrix} v_K \\ v_{K+1} \\ v_{K+2} \\ v_{K+2} \end{bmatrix} \tag{2.69}$$

Equation 2.69 can also be expressed in the partitioned form as shown in the equation (2.70).

$$\begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix} \begin{bmatrix} \underline{P} \\ C\underline{P} \end{bmatrix} = \begin{bmatrix} \underline{V}_1 \\ \underline{V}_2 \end{bmatrix} \tag{2.70}$$

where,

$$\underline{P} = \begin{bmatrix} R_L \\ L_L \end{bmatrix}, \underline{V}_1 = \begin{bmatrix} V_K \\ V_{K+1} \end{bmatrix}, \underline{V}_2 = \begin{bmatrix} V_{K+2} \\ V_{K+3} \end{bmatrix} \quad \text{and}$$

$\underline{A}, \underline{B}, \underline{C}$ & $\underline{D}$ are 2x2 submatrices

since, vector $\underline{P}$ and $\underline{CP}$ in the equation (2.70) are linearly related, equation (2.70) can be reduced to equation (2.71) or (2.72) by matrix reduction technique, and, the unknown line capacitance C is eliminated in the process as well.

$$\left[A - \underline{B}\, \underline{D}^{-1}\, C \right] \underline{P} = \left[\underline{V}_1 - \underline{B}\, \underline{D}^{-1}\, \underline{V}_2 \right] \tag{2.71}$$

or

$$A^1 P = V^1 \tag{2.72}$$

where,

$$A^1 = \left[\underline{A} - \underline{B}\, \underline{D}^{-1}\, \underline{C} \right]; \quad V^1 = \left[\underline{V}_1 - \underline{B}\, \underline{D}^{-1}\, \underline{V}_2 \right]$$

$$\text{and } P = \begin{bmatrix} R_L \\ L_L \end{bmatrix}$$

Equation (2.72) can be solved to give R_L and L_L.

2.3.4 Method 4

In this method, the impedance is determined directly in phasor form from the ratio of the frequency domain values of the fundamental components of the voltage and current by finite transform method [23] . This method has been elaborated in the section (2.2.2.5). The offline performance studies indicate, that acceptable accuracy can be coupled with an operating time of typically three quarters of a cycle of power frequency.

CHAPTER 3

PROPOSED DISTANCE RELAYING ALGORITHM

3.1 INTRODUCTION

In this chapter the algorithm for the protection of the three phase transmission line using the digital computer is presented. The analog voltage and current signals are obtained through conventional P.Ts. and C.Ts. respectively, and after passing through the appropriate circuitary, these signals are transmitted to the digital processor. The detection of the fault is done using cycle by cycle comparison of the voltage signals. After the detection of the fault, the appropriate single phase relaying quantities are selected for subsequent line impedance calculation. The voltage peak and the current peak of the sinusoidal waveforms and their relative phase difference are evaluated from the selected voltage and current signals and their first derivatives. The modulus and the argument of the impedance are calculated from the division of the voltage peak by the current peak and the relative phase difference of the sinusoidal waveforms. Since, the simulated fault data contain only fundamental frequency components, no filters are employed in this algorithm. The three zones protective schemes, which are normally used for the protection of the transmission lines, are discussed. Different types of

relay characteristics and the appropriate signals to obtain these characteristics in the β-plane are discussed and these different threshold characteristics are shown in Figs. (3.3a-3.3k) based upon phase comparison method. To avoid the possibility of mal-operation of the relay due to power swing effects, the relay characteristics such as quadrilateral, elliptical and mho with blinders, which inclose the fault area compactly, are discussed. Finally, the results, shown in the tabulated forms, are examined and discussed, and the merits and demerits of the impedance algorithm are also examined.

The digital relaying system consists of a general purpose high speed minicomputer or microprocessor coupled to a high speed A/D converter. In operation, sample and hold circuits internal to the multiplexer, sample phase to neutral voltages and phase currents 40 times per cycle, i.e. in the interval of 0.5 ms. The A/D converter converts each analog signal to a digital equivalent whereupon its output is transmitted into memory via a direct access channel.

The proposed algorithm is tested on DEC 1090 at I.I.T. Kanpur for all possible faults at several locations in the transmission line and also all possible protective relaying schemes are realized.

3.2 THEORY

The proposed algorithm for the protection of the transmission line can be sub-divided into the following sequence of operations :

1. detection of the fault,
2. classification of the fault,
3. selection of single phase relaying quantities,
4. calculation of the impedance, and
5. realization of any desired relay characteristic.

Fault detection is performed using the cycle by cycle comparison scheme as proposed by Mann and Morrison [5]. The counters such as NOFR, NOFY and NOFB are assigned to red, yellow and blue phase voltages respectively. The voltage samples in each of the phases are compared to the corresponding samples in the previous cycle by subroutine COMP. If the difference between these two values for a particular phase exceeds a tolerance TOLV (i.e. 0.05 p.u.), the counter for that particular phase is incremented by one. When any of the counters exceeds a value CV (i.e. 5), the system enters into the fault detection mode. On the otherhand, if the difference between two voltage samples, found by above comparison is less than TOLV, the counter for that particular phase is decremented

by one, if it is not already zero.

Zero sequence values of the voltage and the current are scanned by subroutine SAMP and are stored in the memory.

Once the fault is detected, the next job is to distinguish between two groups of faults, i.e. the phase faults and the ground faults. This is performed by subroutine FTYPE, in which cycle by cycle comparison is done for zero sequence voltages. If the difference between this value and the corresponding value in the previous cycle exceeds the preset value TOLZ (i.e. 0.005p.u.), the fourth counter, NOFG, assigned for ground, is incremented by one. On the otherhand if this difference is less than the above preset value, counter is decremented by one, if it is not already zero. When the counter value equals or exceeds to CZ (i.e.5), the fault is detected as ground fault.

After the classification of fault, the appropriate quantities of the voltages and the currents,i.e. the equivalent single phase relaying quantities are selected. The delta quantities for phase faults and phase voltages and zero sequence compensated phase currents for ground faults are needed for impedance calculation. This is performed by subroutine SELCT. The aim of this subroutine is to determine which two of the red,

yellow or blue phases or ground are to be used to derive the equivalent single phase quantities. If a counter has value 5, then the phase it represents is considered to be involved in the fault, if a counter has value 0 or 1, the phase is not involved in the fault. If the value is 2 or 3, it is undetermined. As phase faults include three phase symmetrical faults, line to line faults, line-line to ground faults, this algorithm treats them as the same. For example a RYG fault can be treated as RY or YG or RG fault, but it is preferable to treat it as RY fault rather than RG or YG fault since impedance calculation is more accurate for phase faults.

The voltage peak and the current peak of selected sinusoidal waveforms and also their relative phase difference are evaluated from the samples and their first derivatives, solved numerically using backward difference method (shown in Appendix AII). The modulus and the argument of the impedance are calculated from the division of the voltage peak by the current peak and the relative phase difference of the sinusoidal waveforms of voltage and current respectively.

The tripping decision is taken from the relay criteria, i.e. the relay gives a trip signal if the impedance lies within the tripping area of that relay for specified zone.

The time delays provided, for zone2 and zone 3 operations, are 10 ms and 20 ms respectively. Any desired relay characteristic is realized depending upon the requirements.

The flow charts for the proposed relaying schemes are shown in Fig. (3.1a) - (3.1e).

3.3 THREE ZONE PROTECTION OF THE TRANSMISSION LINE

Different types of possible faults in a 3-phase transmission line are as follows :

1. three phase symmetrical fault, i.e. only one in no.,
2. single line to ground faults, i.e. 3 in no.,
3. line to line faults, i.e. 3 in no. and
4. double line to ground faults, i.e. 3 in no..

Therefore, there are total of ten faults. These faults can further be classified into two categories such as :

1. ground faults - which include only single line to ground faults, and
2. phase faults - which include rest of the faults.

In general, the fault takes place involving more than one phase through fault resistance, which include arcing resistance of

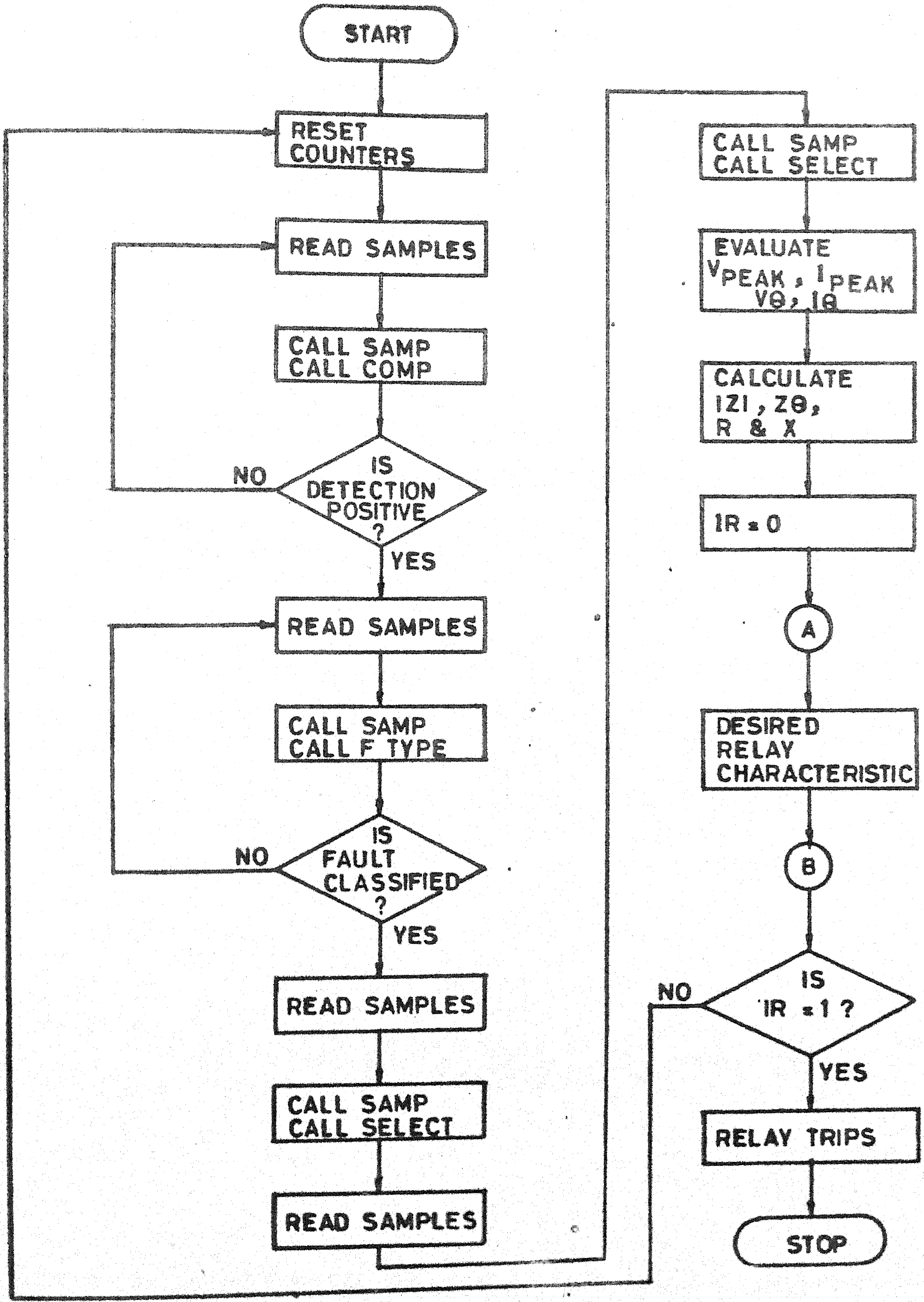


FIG. 3.1.a FLOW CHART OF PROPOSED RELAYING SCHEME

(For A & B go to figs- (3.4.a) —(3.4.f)).

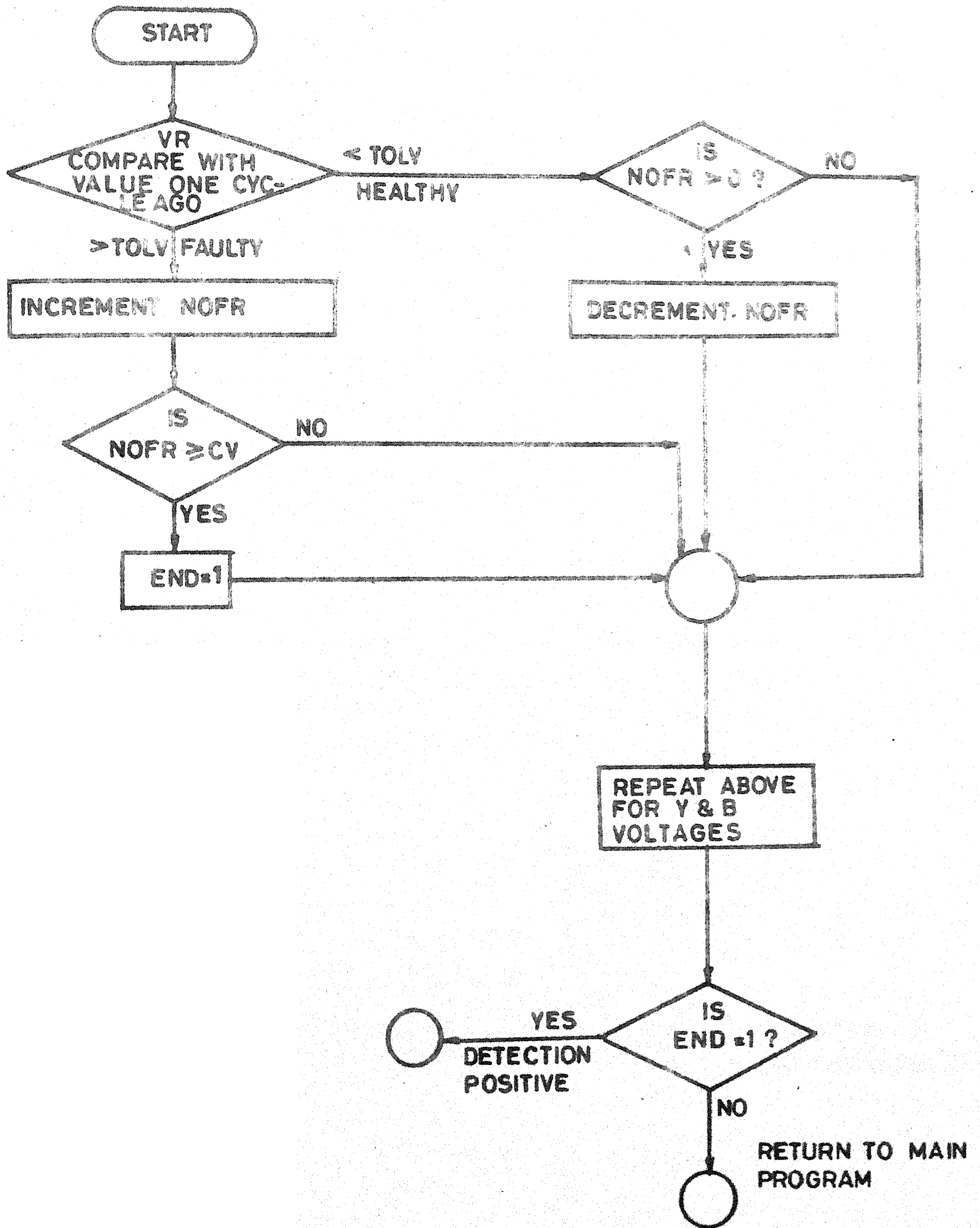


FIG. 3.1.b SUBROUTINE COMP

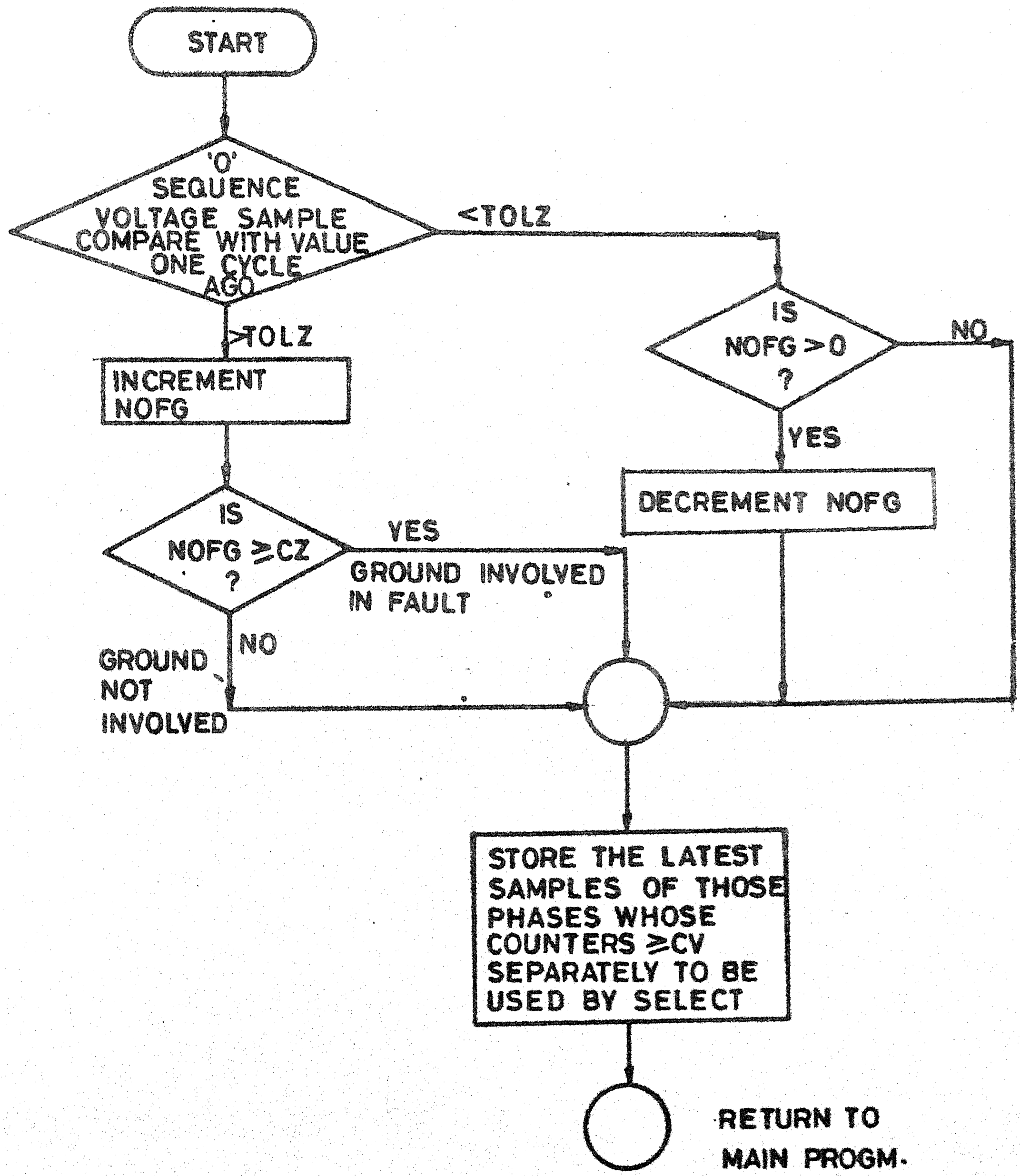


FIG. 3.1.c SUBROUTINE FTYPE

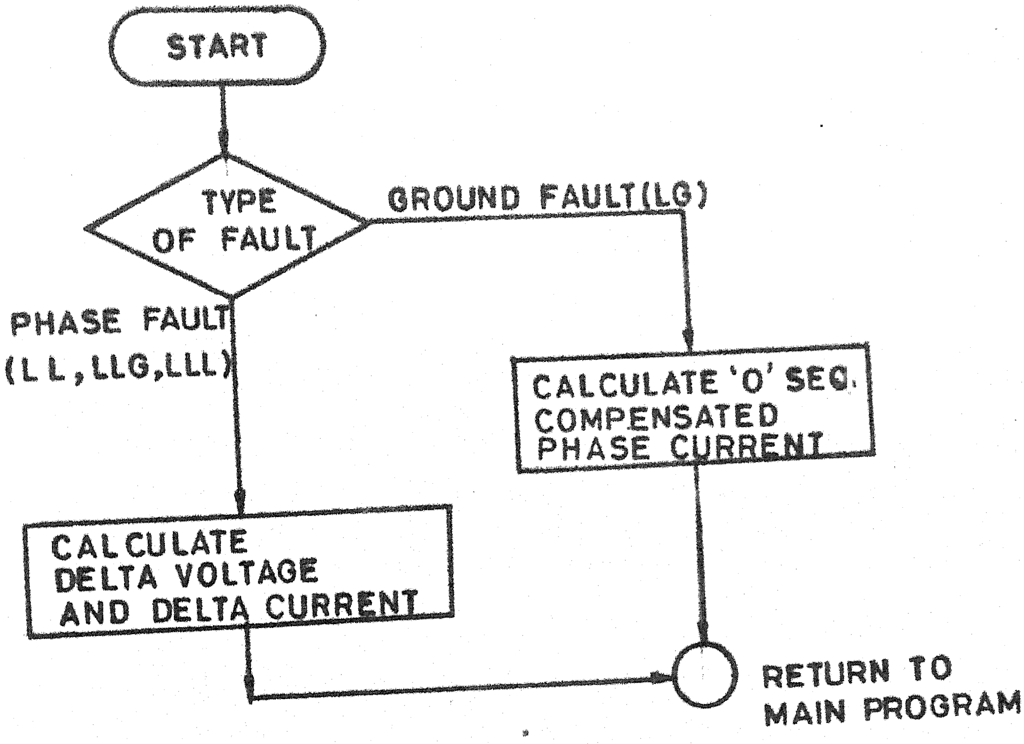


FIG. 3.1.d SUBROUTINE SELECT

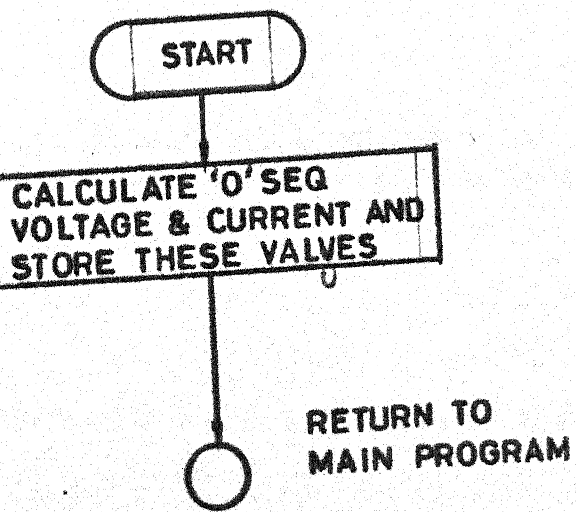


FIG. 3.1.e SUBROUTINE SAMP

the arc path, tower footing resistance and resistance of ground return as the case may be, thus, the relay sees the impedance more than the actual value and hence over-reaching of the relay may take place. To avoid any maloperation of the relay because of the over reaching, normally the reach of the relay is set to 80%-90% length of the transmission line is being protected. Usually, a 3 zone protective scheme is adopted for the protection of the transmission line, the first zone covers only upto 80%-90% length of the first section and operates instantaneously, The zone 2 covers entire length of first section and upto 30% - 50% length of the second section and operates with some time delay and the zone 3 covers the entire length of the first and the second sections and operates with some more time delay. The zone 2 provides the primary protection to the first section from 80% - 90% to 100% of its length, viz the length of the first section not being covered by the first zone, and for other parts of sections it provides back up protection. The zone 3 provides back up protection to the entire lengths of the first and second sections and also acts as a starting element of the relay. This scheme is shown in Fig. 3.2.

The voltage and the current samples at the relay locations are obtained through PTs and CTs respectively. The

replica impedance or set impedance is given by,

$$Z_R = Z_1 \quad \times \frac{\text{C.T. ratio}}{\text{P.T. ratio}}$$

where Z_1 is the line impedance. The set impedances for all the three zones Z_{R1}, Z_{R2} and Z_{R3} respectively, are,

$$Z_{R1} = 0.8 \times Z_{11} \times \frac{\text{C.T. ratio}}{\text{P.T. ratio}},$$

$$Z_{R2} = (Z_{11} + 0.5 \times Z_{12}) \times \frac{\text{C.T. ratio}}{\text{P.T. ratio}} \quad \text{and}$$

$$Z_{R3} = (Z_{11} + Z_{12}) \times \frac{\text{C.T. ratio}}{\text{P.T. ratio}}$$

where, Z_{11} and Z_{12} are the impedances of the first section and the second section respectively.

For impedance calculation, the delta quantities of the voltages and the currents are used for the phase faults and phase voltages and zero sequence compensated phase currents are used for the ground faults, viz.

$$Z = \frac{V_a - V_b}{I_a - I_b} \text{ for phase fault}$$

$$Z = \frac{V_a}{I_a + K.I_o} \quad \text{for ground fault}$$

where I_o is zero sequence current and K. is known as compensating current coefficient, which is given by,

$$K = \frac{(Z_0 - Z_1)}{Z_1}$$

where Z_o is the zero sequence impedance of the line and

Z_1 is the positive sequence impedance of the line.

3.4 TYPES OF DISTANCE RELAYS

Different types of classical relays and signals to obtain these characteristics are given in the following table.

Characteristics	Amplitude Comparison		Phase Comparison	
	Operate (S_1)	Restrain (S_2)	Measuring (S_1')	Polarizing (S_2')
Directional	IZ_R+V	$V-IZ_R$	IZ_R	V
	(Z_R+Z)	$(Z-Z_R)$	(Z_R)	(Z)
Plain Impedance	IZ_R	V	IZ_R-V	IZ_R+V
	(Z_R)	(Z)	(Z_R-Z)	(Z_R+Z)

table continued

Characteristics	Amplitude Comparison Operate (S_1)	Amplitude Comparison Restrain (S_2)	Phase Comparison Measuring (S_1')	Phase Comparison Polarilizing (S_2')
Angle Impedance (ohm)	$2IZ_R-V$ $(2Z_R-Z)$	V (Z)	IZ_R-V (Z_R-Z)	IZ_R (Z_R)
Angle admittance (mho)	IZ_R (Z_R)	$2V-IZ_R$ $(2Z-Z_R)$	IZ_R-V (Z_R-Z)	V (Z)
Offset mho	$I(Z_R-Z_o)$ (Z_R-Z_o)	$2V-I(Z_R+Z_o)$ $(2Z-(Z_R-Z_o))$	IZ_R-V (Z_R-Z)	$V-IZ_o$ $(Z-Z_o)$

As amplitude comparator, the tripping criteria is given by,

$$|S_1| \geq |S_2|$$

and at threshold,

$$|S_1| = |S_2| ,$$

where S_1 and S_2 are two signals, i.e. the operating and the restraining to the relay respectively.

As phase comparator, the tripping criteria is given by,

$$-90^{\circ} \leq \Psi \leq 90^{\circ},$$

and at the threshold, $\Psi = \pm 90^{\circ}$,

where Ψ is the angle between two signals S_1' and S_2' to the relay ($\Psi = \angle S_2' - \angle S_1'$)

To obtain the reactance characteristic from the ohm relay characteristic, the angle of the polarizing signal is set to 90° i.e., the replica impedance angle is set equal to 90°. Basically, this relay is used for ground faults as it is not affected by the fault resistance. This relay is always accompanied by fault detecting and directional relays such as mho relay, which combines the function of starting and directional feature in a single unit.

To obtain the restricted characteristics and hence an another group of threshold characteristics, the threshold angle is set to an angle β, which is less than 90°. The conditions for the restricted threshold characteristics (phase comparison) are given by,

$$-\beta \leq \Psi \leq \beta \quad \text{for tripping,}$$

and at threshold, $\Psi = \pm \beta$,

where $\beta < 90^\circ$

The another group of relay characteristics, obtained by restricting the classical relay characteristics, includes the following :

1. restricted directional,
2. restricted ohm,
3. restricted mho, i.e. elliptical characteristic,
4. combination of restricted directional and restricted ohm, i.e. quadrilateral characteristic and
5. mho relay with blinders.

The threshold characteristics, as mentioned above, are shown in Figs. (3.3a) - (3.3k) for the set impedance Z_R. For the three zone protective scheme, Z_R is replaced by appropriate set impedances, i.e. it is replaced by Z_{R1}, Z_{R2} and Z_{R3} for first, second and third zone respectively.

Flow charts for 3 zones protective schemes, such as plain impedance with directional unit, mho relay with offset characteristic as zone 3 unit, reactance relay alongwith mho relay as directional unit, elliptical relay, quadrilateral relay and mho relay with blinders, are shown in Figs. (3.4a)-(3.4f),

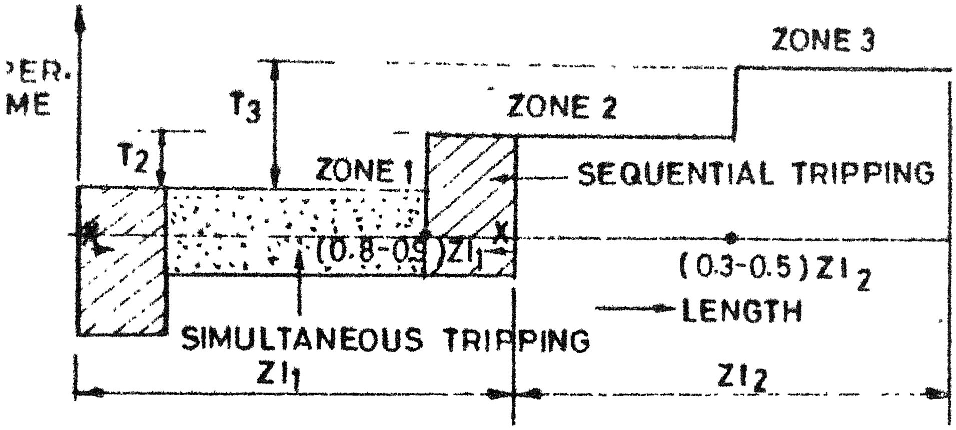


FIG. 3.2 THREE ZONES PROTECTIVE SCHMES

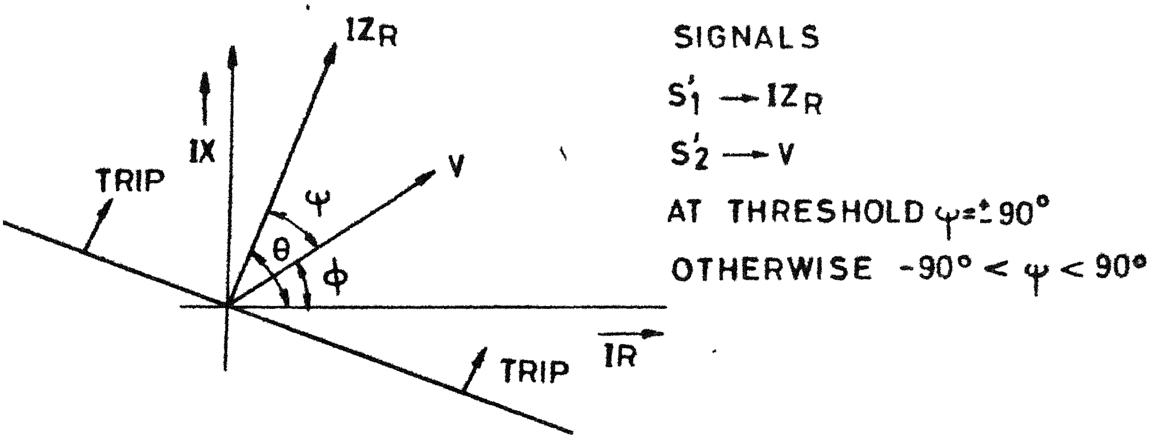


FIG. 3.3a DIRECTIONAL RELAY

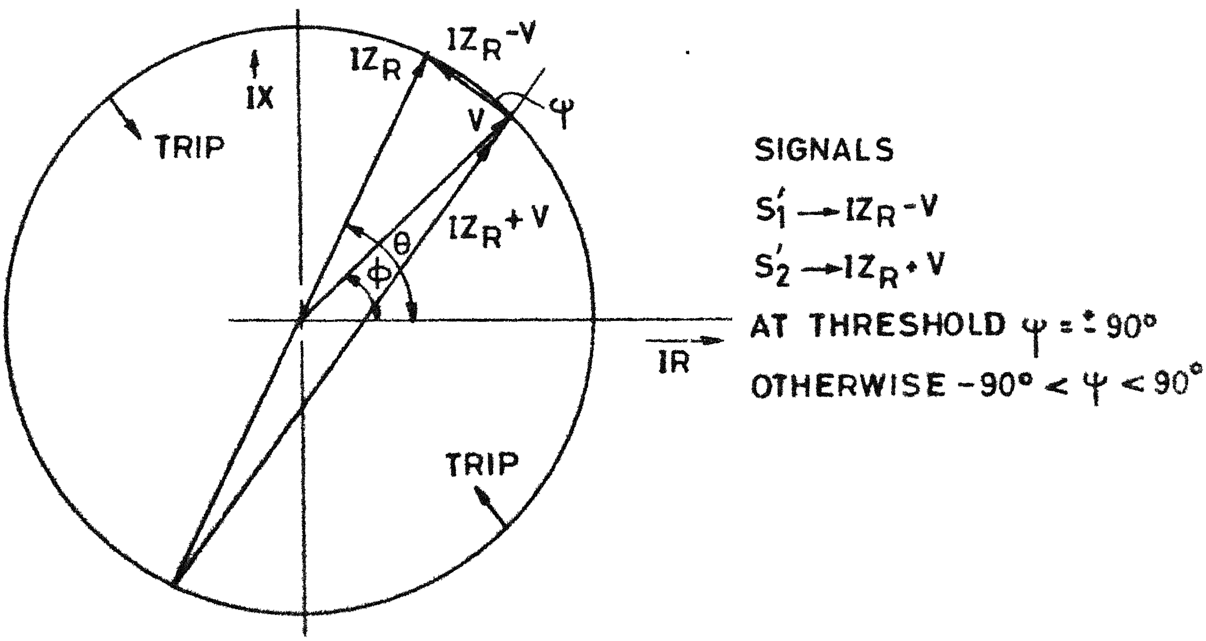
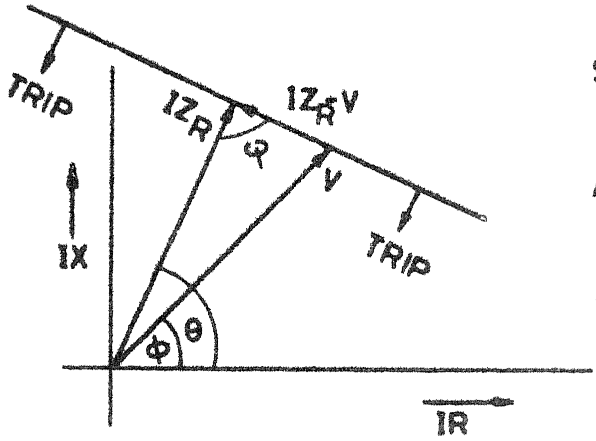


FIG. 3.3b PLAIN IMPEDENCE RELAY



SIGNALS

$S_1' \rightarrow IZ_R - V$

$S_2' \rightarrow IZ_R$

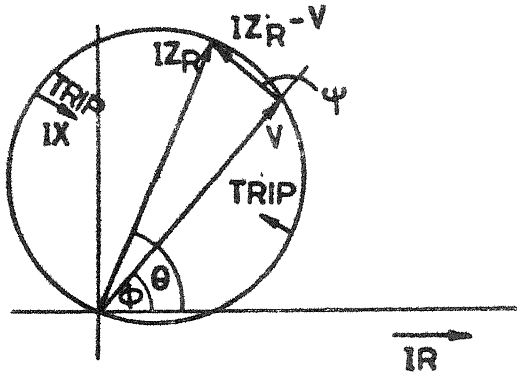
AT THRESHOLD

$\psi = \pm 90^\circ$

OTHERWISE

$-90^\circ < \psi < 90^\circ$

FIG. 3.2.c OHM RELAY (i.e. angle impedance relay)



SIGNALS

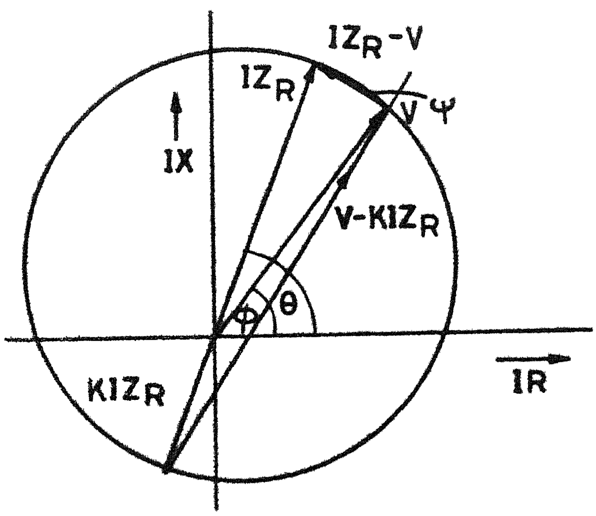
$S_1' \rightarrow IZ_R - V$

$S_2' \rightarrow V$

AT THRESHOLD $\psi = \pm 90^\circ$

OTHERWISE $-90^\circ < \psi < 90^\circ$

FIG. 3.2.d MHO RELAY (i.e. angle admittance relay)



SIGNALS

$S_1' \rightarrow IZ_R - V$

$S_2' \rightarrow KIZ_R + V$ ($K \angle 1$)

AT THRESHOLD $\psi = \pm 90^\circ$

OTHERWISE $-90^\circ < \psi < 90^\circ$

FIG. 3.2.e OFFSET MHO RELAY

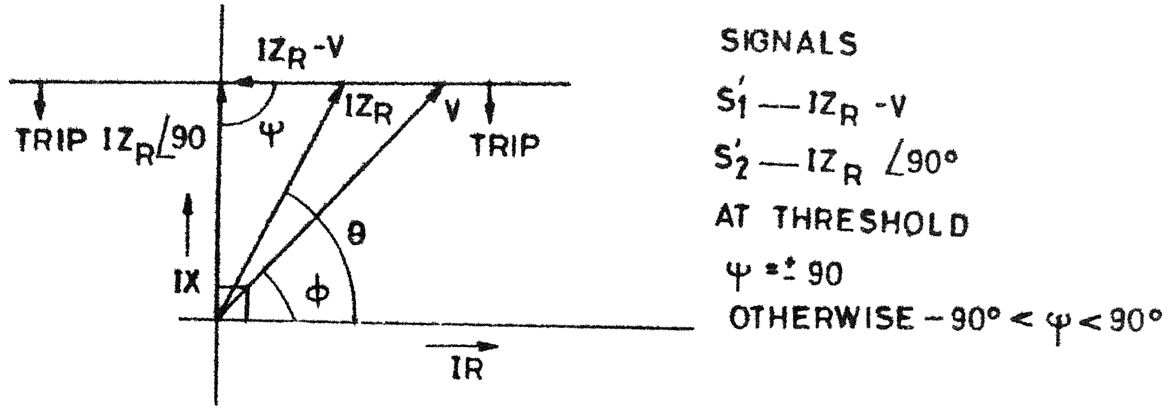


FIG. 3.2.f REACTANCE RELAY

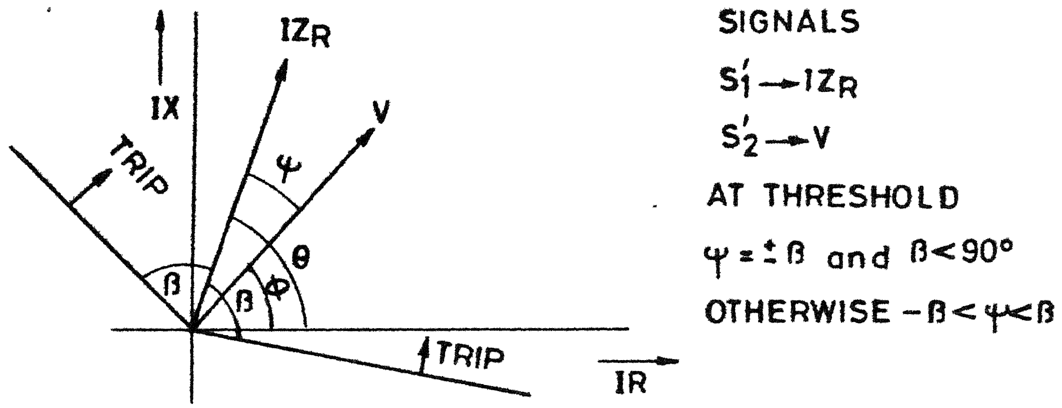


FIG. 3.2.g RESTRICTED DIRECTIONAL RELAY

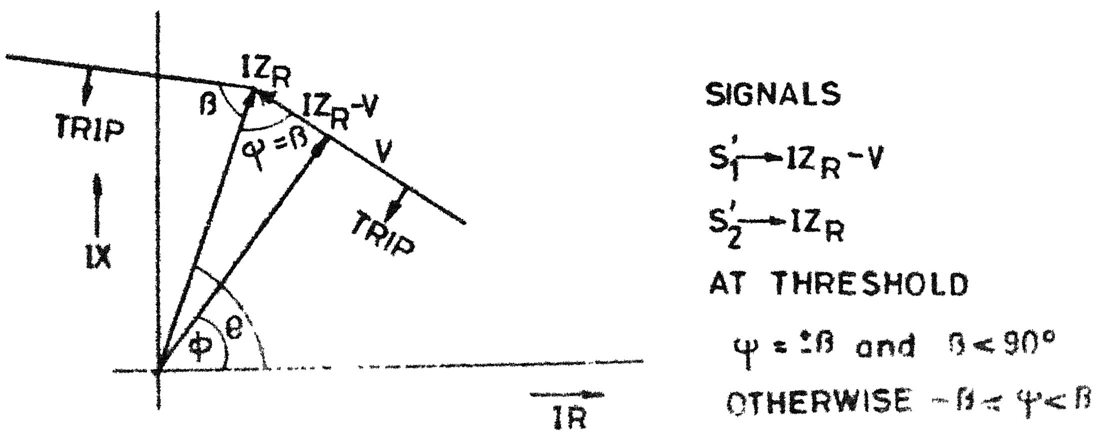


FIG. 3.2.h RESTRICTED OHM RELAY

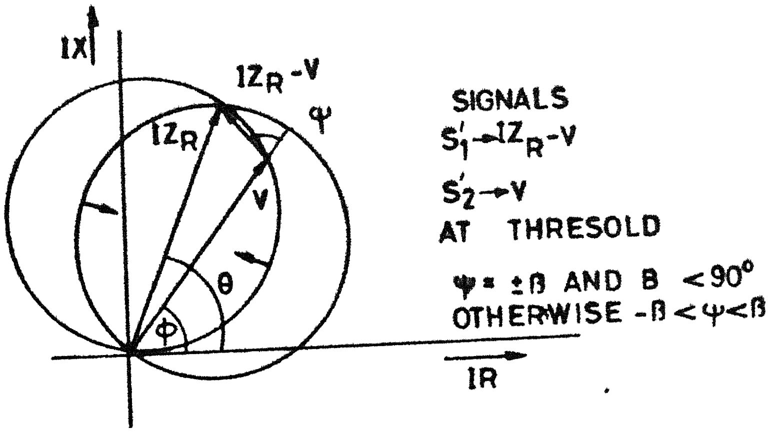


FIG. 3.2.i ELLIPTICAL RELAY (Restricted MHO relay)

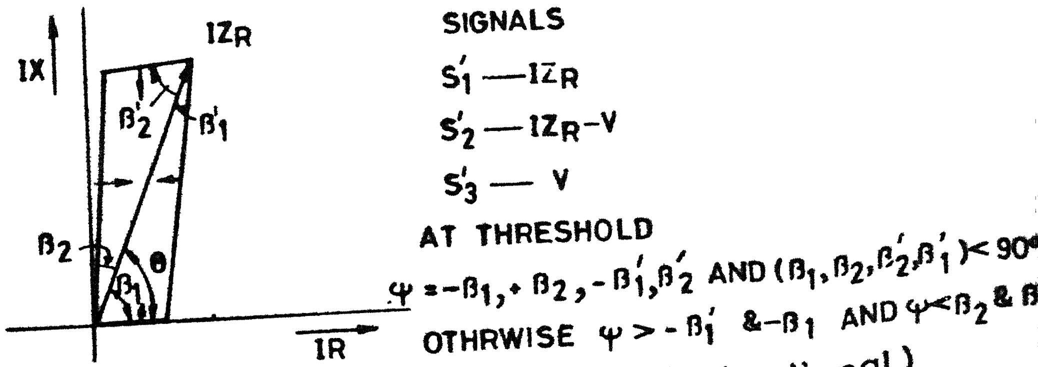


FIG. 3.2.j QUADRILATERAL RELAY (Restricted ohm & directional)

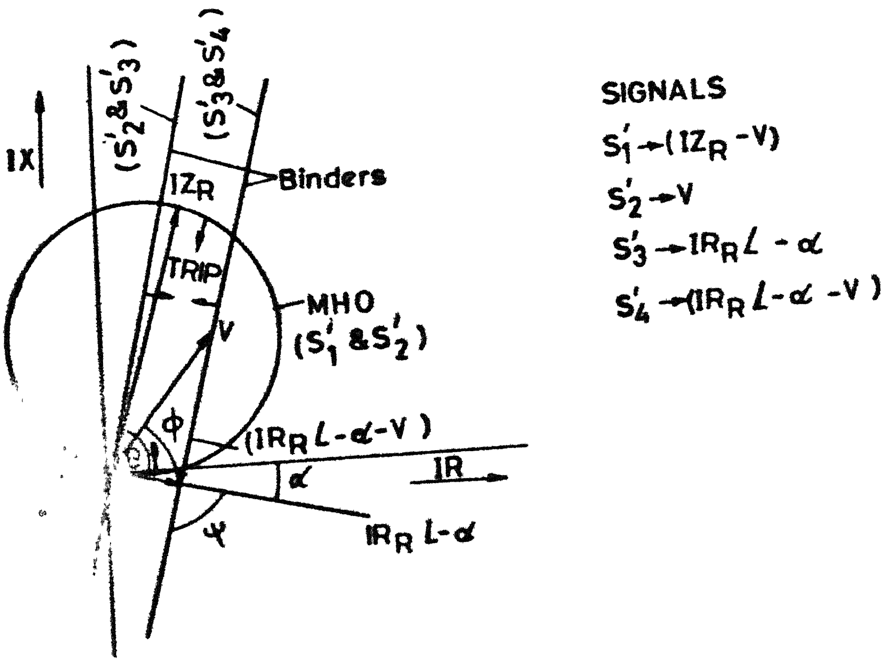


FIG. 3.2.k MHO WITH BLINDERS

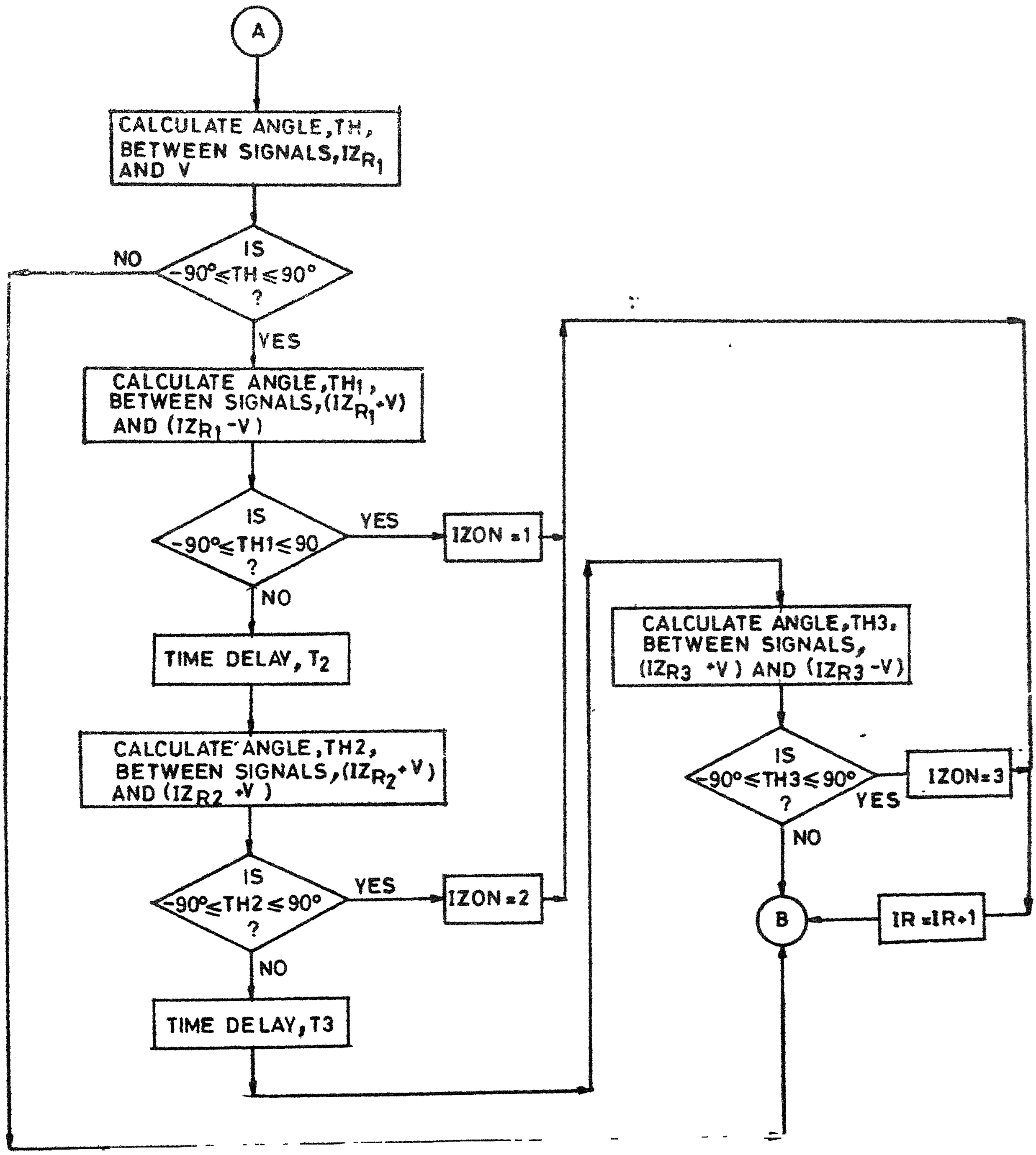


FIG. 3.4.a PLAIN IMPEDENCE RELAY

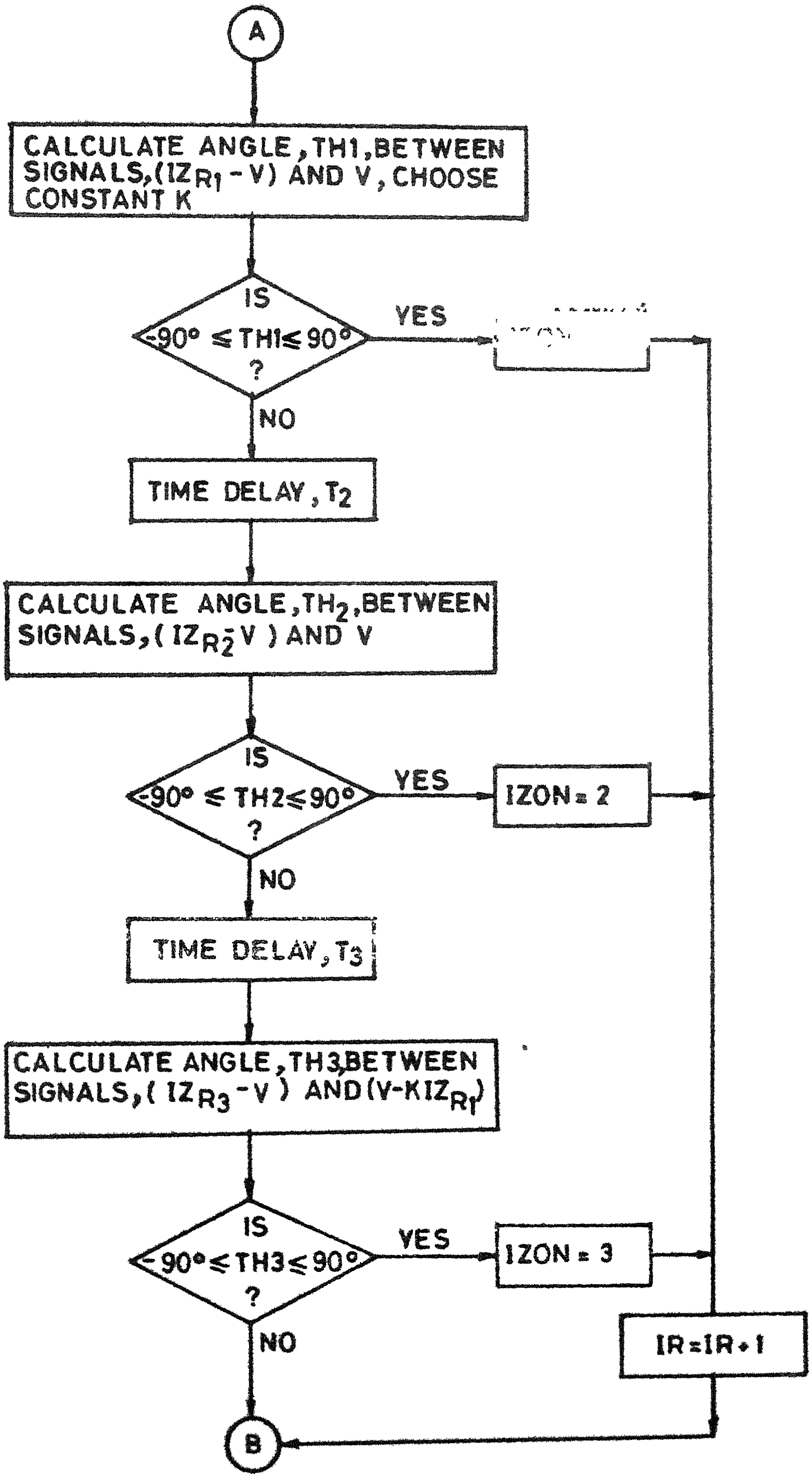


FIG. 3.4.b MHO RELAY (i.e. angle admittance relay)

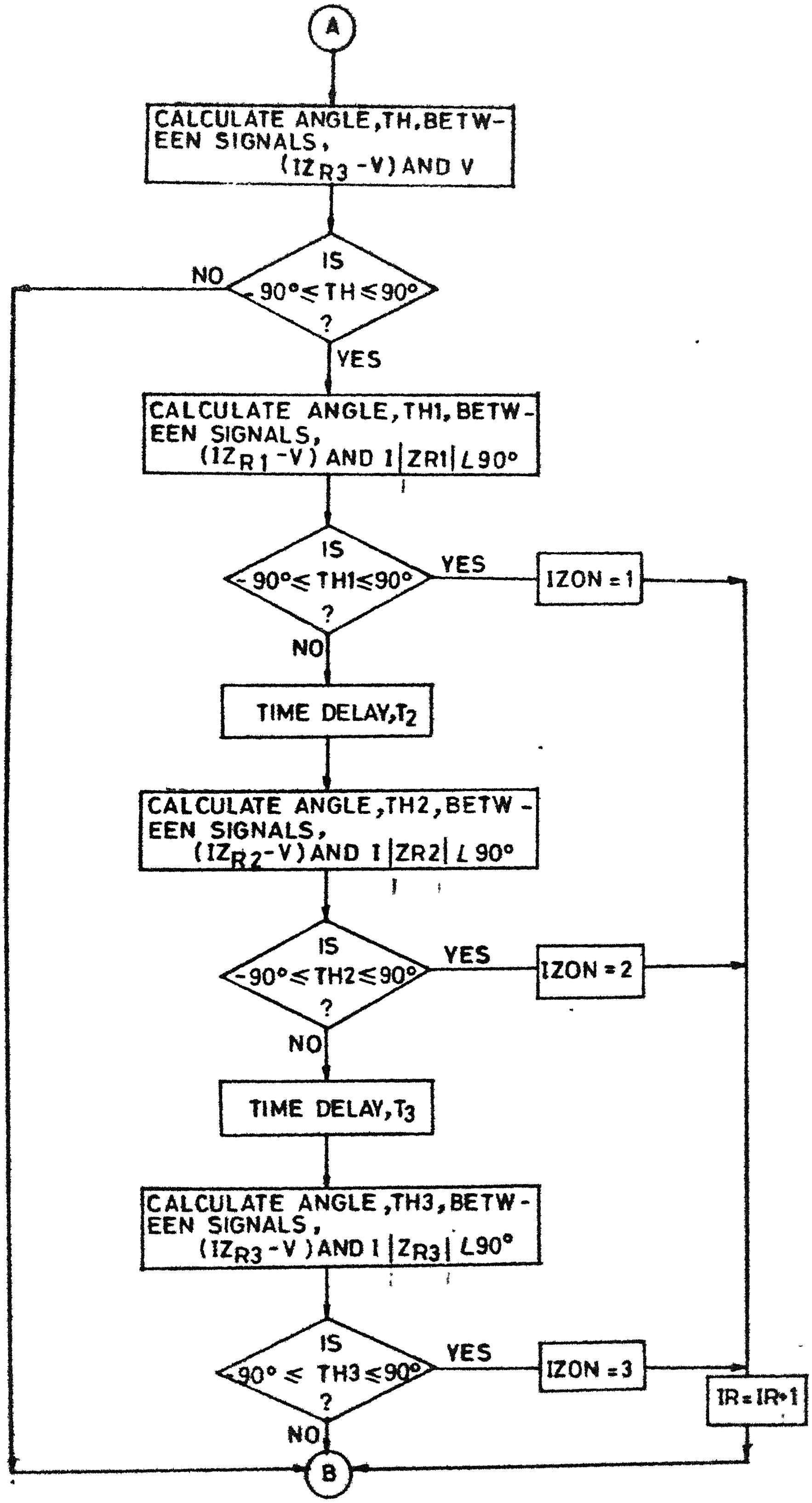


FIG. 3.4.c REACTANCE RELAY

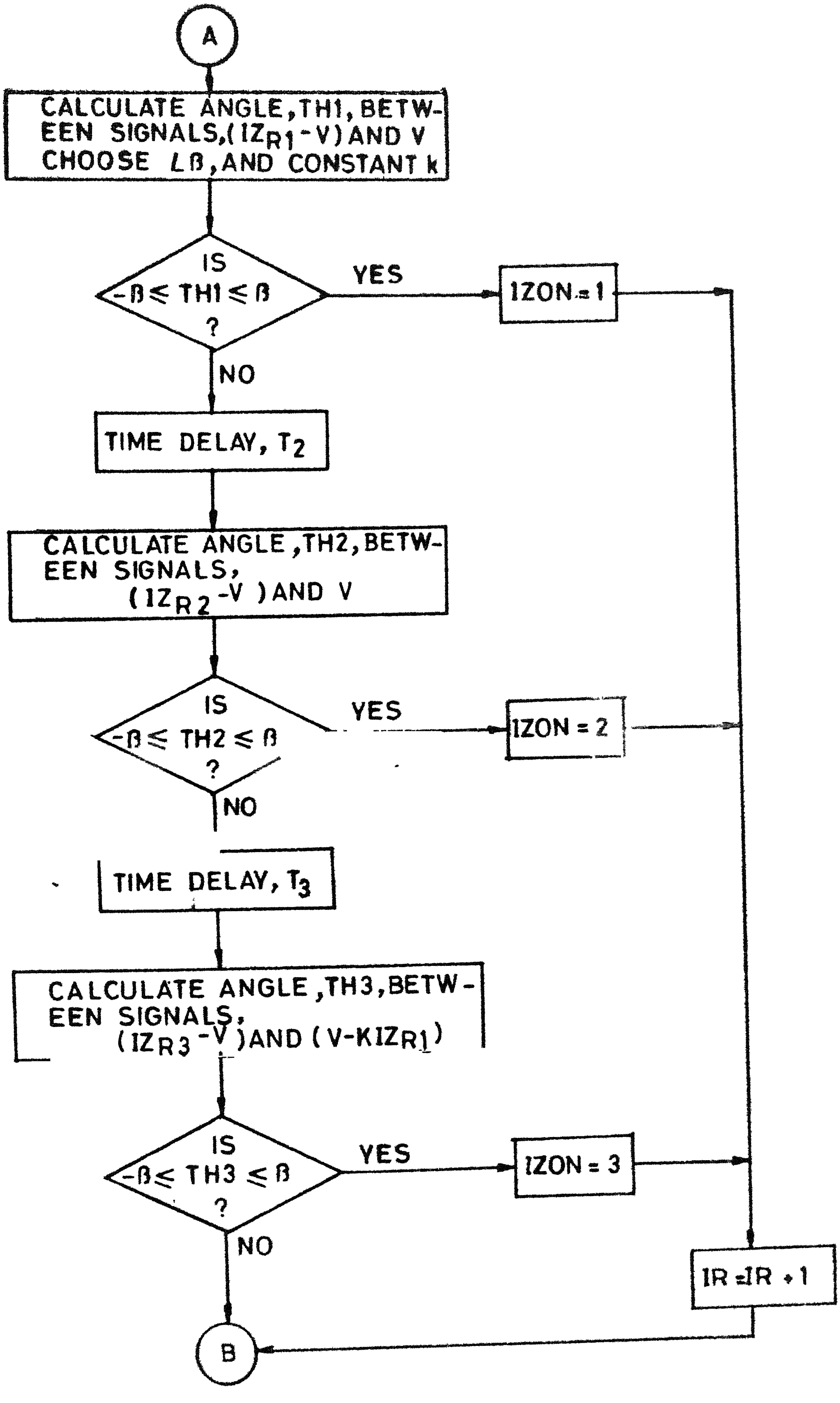


FIG 3.4.d ELLIPTICAL RELAY

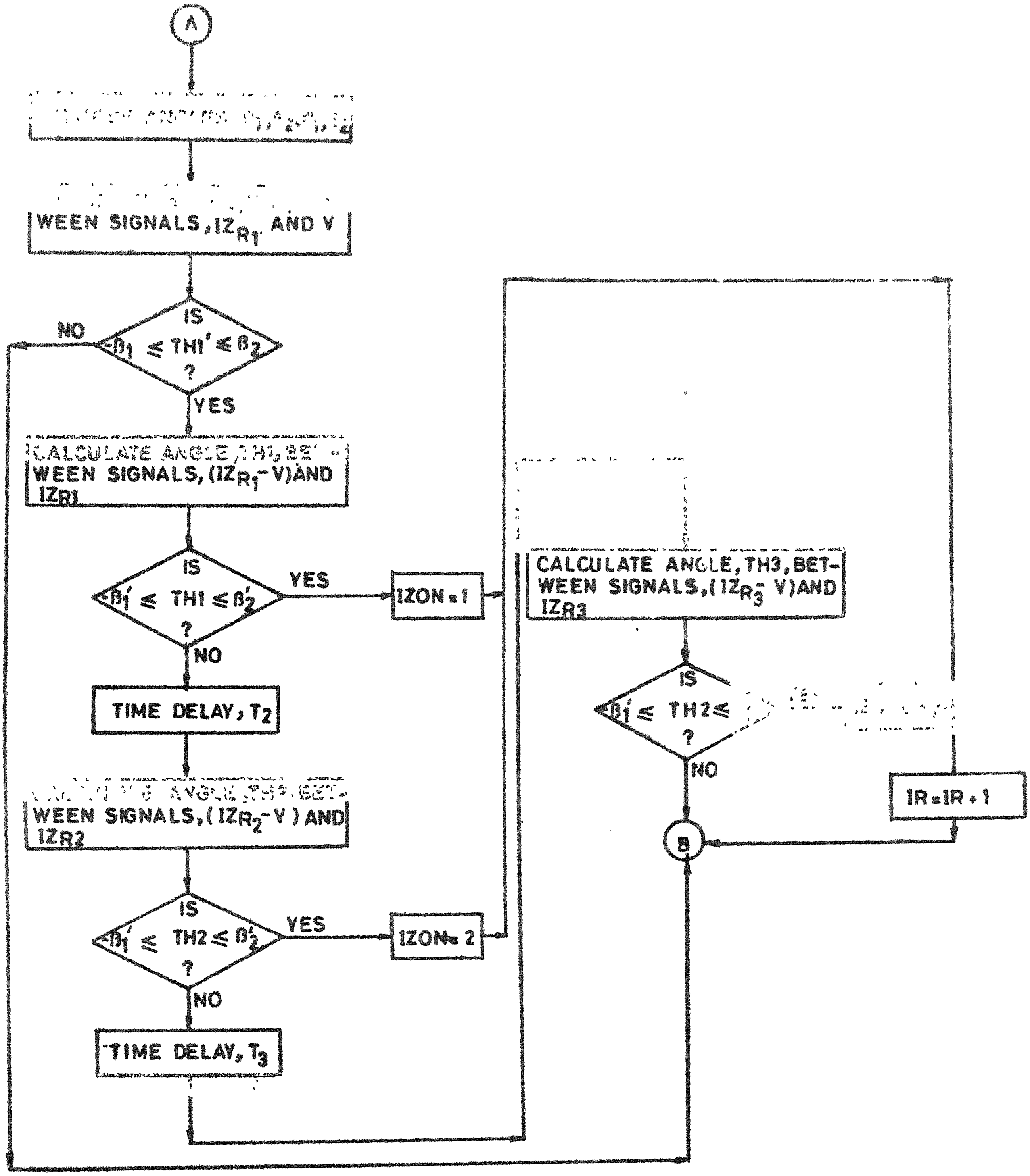


FIG. 3.4.e QUADRILATERAL RELAY

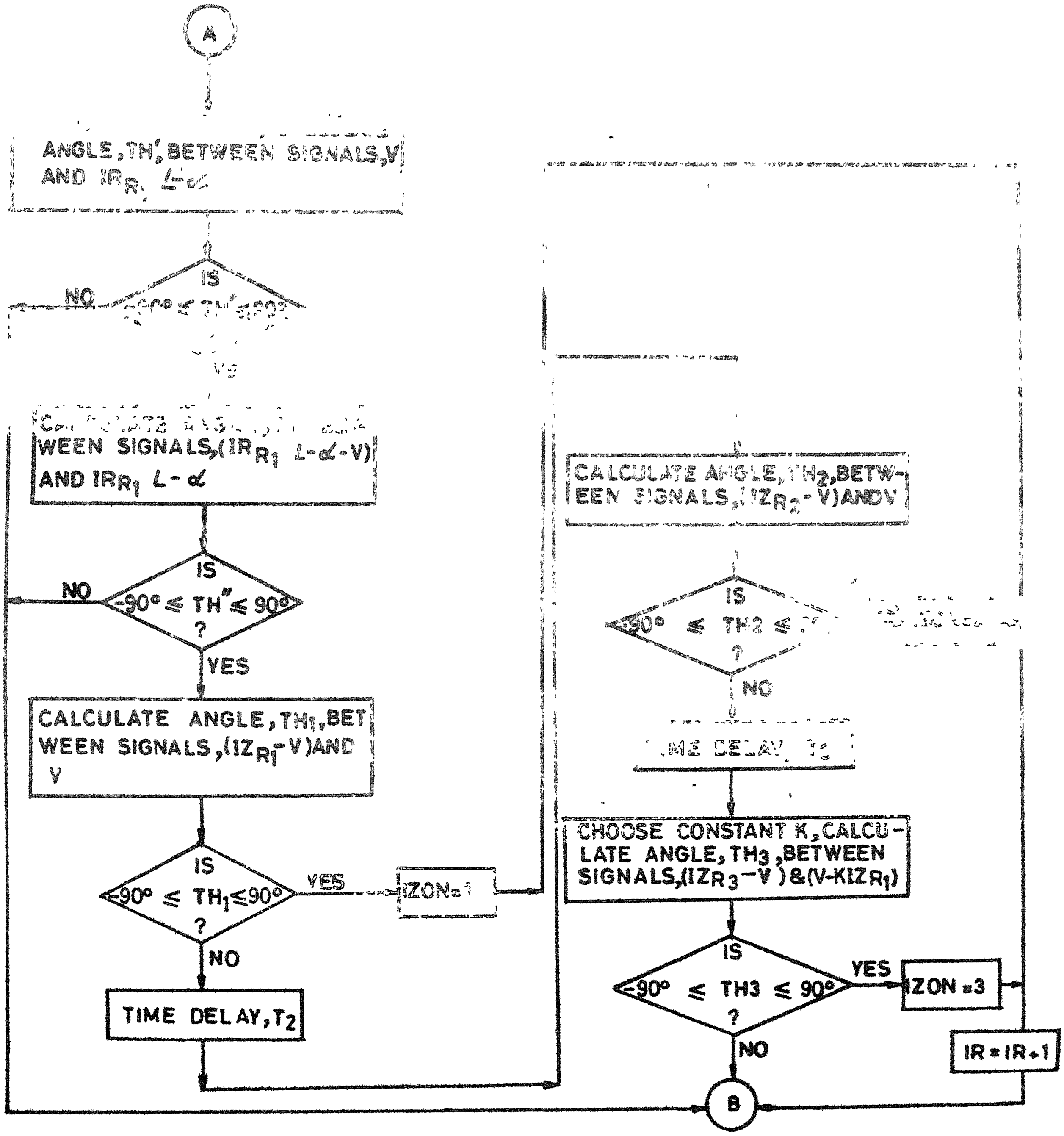


FIG.3.4.f MHO RELAY WITH BLINDERS

3.5 RESULTS AND DISCUSSIONS

The proposed three phase relaying scheme has been tested for the transmission line (App. I) with the simulated fault data for all types of faults, i.e. single line to ground faults, double line to ground faults, line to line faults and three phase symmetrical faults. The errors in the calculation of modulus of the impedance and its phase angle are approximately within $\pm$ 10% and $\pm$ 12 deg. respecitvely. The calculated line impedances and actual impedances, for several locations of faults are shown in table31.

In the simulated fault data, the fault impedance is neglected and dc offset and h.f. transients in the post fault waveforms are also neglected, thus no filter is being realized.

After the occurance of the fault, only seven samples are needed for fault detection and subsequent impedance calculation. The tripping signal is obtained based upon the criteria of any desired relay characteristics, several three zones relaying schemes have been realized. The time delays provided, for zone 2 and zone 3 tripping, are 10 ms and 20 ms respectively. The operating time of the relay is found to be approximately 10 ms for zone 1 tripping.

TABLE 3.1

Type of fault	p.u. length	Calculated line impedance p.u. R (p.u.)	X (p.u.)	Z (p.u.)	∠Z deg.	Actual line impedance (p.u.) R (p.u.)	X (p.u.)	Z (p.u.)	∠Z deg.	% error in |Z|	error in ∠Z (deg.)
	0.2	0.0003	0.0026	0.0026	84.55	0.0007	0.0026	0.0027	74.11	3.85	-10.44
	0.4	0.0005	0.0052	0.0052	84.55	0.0015	0.0052	0.0054	74.02	3.85	-10.53
LG	0.6	0.0008	0.0078	0.0078	84.55	0.0022	0.0076	0.0079	73.49	1.42	-11.06
	0.8	0.0010	0.0104	0.0104	84.55	0.0029	0.0098	0.0103	73.39	0.96	-11.16
	1.0	0.0013	0.0130	0.0131	84.55	0.0035	0.0120	0.0125	73.71	4.58	-11.84
	0.2	0.0003	0.0026	0.0026	84.55	0.0001	0.0024	0.0024	86.66	-7.69	2.11
	0.4	0.0005	0.0052	0.0052	84.55	0.0003	0.0049	0.0049	86.76	-5.77	2.21
LL	0.6	0.0008	0.0078	0.0078	84.55	0.0004	0.0073	0.0073	86.81	-6.41	2.26
	0.8	0.0010	0.0104	0.0104	84.55	0.0005	0.0098	0.0098	86.84	-5.77	2.29
	1.0	0.0013	0.0130	0.0130	84.55	0.0057	0.0122	0.0122	78.85	-6.87	-5.70
	0.2	0.0003	0.0026	0.0026	84.55	0.0005	0.0022	0.0023	78.15	-11.54	-6.40
	0.4	0.0005	0.0052	0.0052	84.55	0.0009	0.0045	0.0045	79.10	-13.46	-5.45
LLG	0.6	0.0008	0.0078	0.0078	84.55	0.0004	0.0073	0.0073	86.81	-6.41	2.26
	0.8	0.0010	0.0104	0.0104	84.55	0.0005	0.0098	0.0098	86.83	-5.77	2.28
	1.0	0.0013	0.0130	0.0130	84.55	0.0007	0.0122	0.0122	86.85	-6.87	2.30
	0.2	0.0003	0.0026	0.0026	84.55	0.0005	0.0025	0.0026	79.83	0.00	-4.72
	0.4	0.0005	0.0052	0.0052	84.55	0.0009	0.0051	0.0052	79.85	0.00	-4.70
LLL	0.6	0.0008	0.0078	0.0078	84.55	0.0014	0.0076	0.0077	79.85	0.013	-4.70
	0.8	0.0010	0.0104	0.0104	84.55	0.0018	0.0102	0.0103	79.85	0.96	-4.70
	0.0	0.0013	0.0130	0.0130	84.55	0.0007	0.0122	0.0122	86.91	-6.89	2.36

CHAPTER 4

CONCLUSIONS

This chapter is aimed at reviewing the siginificant results obtained during the course of this work and making a few suggestions for future scope in this field of protection.

In chapter one, it is stated that larger amount of power can be transmitted without loss of stability, when the fault is cleared in a shorter time. Thus one of our major aims is to make the relay fast in operation alongwith other merits. The digital computer protection of transmission lines possesses several merits such as faster in operation, flexibility in obtaining any threshold characteristics and self checking facilities against hardware failures. In the same chapter, the overview of the works done by several authors in the field of digital protection so far, have been outlined in brief.

The filters are employed to extract the fundamental frequency components from post fault complex waveforms as the distance impedance relay algorithms are based upon only the fundamental frequency components of voltage and current, some

of these algorithms and filters are presented in chapter 2.

The algorithm for the protection of three phase transmission line based upon the predictive calculation of the impedance is being discussed in detail and also tested for all types of faults on transmission line at different locations. The line impedance calculation yields a high accuracy, i.e. within $\pm$ 10%. This is inspite of considering only the first term in the expression for numerical differentiation. Even, better accuracies can be realized by considering a few more terms in the above expression. A number of 3 zones protective relaying schemes such as plain impedance relay with directional unit, mho relay with offset as 3rd zone unit, reactance relay with mho as starting element, quadrilateral relay (i.e. restricted directional and restricted ohm relay), elliptical relay (i.e. restricted mho relay) and mho relay with blinders, have been realized with time delays being 10 ms and 20 ms for zone 2 and zone 3 tripping. The special relay characteristics such as quadrilateral and elliptical, which are suitable for long heavily loaded line, offer the best threshold characteristics as they enclose fault area compactly.

The operating time of the relay, for zone 1, is found to be approximately 10 ms for different types of faults.

The actual operating time of the relay may include the time delays caused in A/D converter, multiplexer and appropriate filtering.

This algorithm for impedance calculation takes lesser time than that in other algorithms as the peaks of the sinusoidal voltage.and current are predicted before their actual occurance, but this algorithm accepts only fundamental components of the voltage and the current signals. Although, theories of filters have been discussed but, in the present work, no such filters are employed as the simulated fault data contain only fundamental components.

The future work may include the harmonics components in addition to the fundamental frequency components in the simulated fault data and realization of appropriate analog and/or digital filters to extract the fundamental frequency components. The work may also be extended with the implementation of actual scheme by designing complete hardware so as obtain digital on line protection.

The installation of single unit digital computer in power station finds the applications in the fields, besides the protection of the transmission lines, such as protection of the generator against the loss of excitation and windings

faults, control of reactive power (i.e. control of terminal voltage) and protection of transformers, bus-bars and other equipments installed in the sub-station and also load dispatching and data logging.

A very fast relay scheme can be developed using travelling wave phenomenon wherefrom the post fault waveforms of the voltage and current fundamental components are suppressed by appropriate filters thus working with the transient components.

APPENDIX I

Transmission line (Singrauli to Kanpur, 400 kV SC) data which is used for testing the proposed protective scheme .

Base : 100 MVA

Length of transmission line : 456 Kms

Line parameters :

Positive sequence resistance, R_1 = 0.00927 p.u.

Positive sequence reactance, X_1 = 0.09427 p.u.

Zero sequence resistance, R_0 = 0.08117 p.u.

Zero sequence reactance, X_0 = 0.27419 p.u.

Source impedance (3x210 MVA) :

Zero sequence reactance, X_0 = 0.016

Direct axis subtransient reactance, X_d'' = 0.03 p.u.

Direct axis transient reactance, X_d' = 0.0412 p.u.

APPENDIX II

DIFFERENTIATIONS FORMULAE

The basic central difference expression for the derivative [4]

$$hy'_k = (\mu\delta - \frac{1}{6}\mu\delta^3 + \frac{1}{30}\mu\delta^5)\, y_k \qquad (AII.1)$$

where ∇, μ and δ are the standard notations for the operations of backward differencing, central differencing and averaging respectively and h is step size, and y stands for v or i.

Using the first term only

$$h\, y'_k = \frac{1}{2}(y_{k+1} - y_{k-1}) \qquad (AII.2)$$

and with a second-term

$$h\, y'_k = -\frac{1}{12}(y_{k+2} + \frac{2}{3}y_{k+1} - \frac{2}{3}y_{k-1} + \frac{1}{12}y_{k-2}) \qquad (AII.3)$$

For backward differences

$$hy'_k = (\nabla - \frac{1}{2}\nabla^2 - \ldots)y_k \qquad (AII.4)$$

Using the first term only,

$$hy'_k = y_k - y_{k-1} \qquad (AII.5)$$

and with a second term

$$hy'_k = \frac{1}{2}(y_k - y_{k-2}) \qquad \text{(AII.6)}$$

Note that (AII.2) and (AII.3) for y'_k involve sample values at times later than t_k, whereas (AII.5) and (AII.6) do not.

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